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Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

« CONTENTS »

Sandstone Types and Their Associated Depositional Environments ..... *E. C. Dapples* 91

Shales and Their Environmental Significance ... *W. C. Krumbein* 101

Environments of Limestone Deposition ..... *Laurence L. Sloss* 109

Coal Partings in Stylolite Seams ..... *B. M. Shaub* 114

The Environmental Significance of Conglomerates ..... *W. H. Twenhofel* 119

Diatomaceous Deposits at Lake Toba..... *H. W. van der Marel* 129

Suggestions to Contributors 135

NOTICE

Second International Conference on Soil Mechanics and Foundation Engineering 138

REVIEW

Andre Cailleux. *Distinction des Galets Marins et Fluviatiles, 1945* ..... *W. J. Plumley* 139

Index 141

Journal of Sedimentary Petrology

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INDEX..... 141

NOTICE

Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal*, should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 17, NO. 3, PP. 91–100
DECEMBER, 1947

The following four papers were presented as part of the symposium before the S.E.P.M. at the Los Angeles meeting of the American Association of Petroleum Geologists. At the time of the selection of the authors of the paper Dr. Krumbein was with the Gulf Oil Corporation and his appointment to Northwestern University was subsequent to his preparation of the paper. It was intended that the paper on limestone would be prepared by Dr. F. B. Plummer. Dr. Plummer's unfortunate death in the early part of 1946 prevented his preparation to the symposium. Subsequently, at the suggestion of Dr. Krumbein, Professor Sloss of Northwestern was requested to prepare the paper on limestone. THE EDITOR

SANDSTONE TYPES AND THEIR ASSOCIATED DEPOSITIONAL ENVIRONMENTS*

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ABSTRACT

Sandstones are classified as platform and basin deposits. Platform sands accumulate under conditions of tectonic stability and steady, uniform currents. Basin sands are deposited in rapidly subsiding areas, or zones of heavy sedimentation where rhythmic current intensities prevail. Each major group is further subdivided into petrographic types whose characteristics are indicated and whose environments of deposition are inferred.

INTRODUCTION

Sandstones constitute that group of fragmental rocks whose average grain size ranges from 1/16 to 2 millimeters. As rocks, their constituents show a great range in bulk composition from mixtures of many mineral species and rock fragments to dominantly mono-mineralic accumulations of quartz, calcite, or gypsum. Some of these monomineralic rocks are a part of the realm of chemical precipitates, and, as a whole form only a small part of those generally designated as sandstones; hence, the following comments are confined to those sandstones, the individual particles of which, have been derived from the weathering of silicate rocks.

The range of environmental conditions coupled with the complex mineralogic and textural variation of sands has resulted in the standard procedure of considering each sandstone a product of its own regimes of source, transportation, and deposition. In many instances each sand has been considered as a separate and distinct unit in a depositional environment, not as a sheet whose lithology and texture varied as the environments of deposition changed. Moreover, sandstones of similar lithology, but widely spaced areally and in time of deposition, have not been grouped into types whose physical environment of deposition appear to have been closely similar. The fact that such repetition of deposits

* Presented before the Society of Economic Paleontologists and Mineralogists, Los Angeles, April, 1947.

possessing common characteristics does occur has led to this attempt to organize sandstones into more or less distinct petrographic classes. The intention at this juncture is not to propose a complete and inflexible classification but merely to provide a preliminary organization which will be modified as additional data are assembled and examined. In this connection the degree of importance of the depositional environments must be clearly established. The reader will note that herein it is considered paramount, and the environments of the source, transportation, and previous deposition are unimportant. Such is doubtless not the case, but, because the acceptable data leave so much to be inferred, the writer has restricted this presentation to information which appears to be reasonably factual. Basically the proposed concept is not original and to some degree has been previously implied, if not stated, by Krynine, Pettijohn, Kay, Bailey, and Jones, who have explored the problem from various points of view.

PLATFORM AND BASIN SANDSTONES

Sandstones composed of silicate rock debris show properties which permit their subdivision into two distinct major groups herein designated as platform and basin types. These somewhat nebulous terms "platform" and "basin" are selected to designate broad areas of similar depositional environments but which differ in being subject to widely divergent tectonic conditions. Hence, "platform deposit" means one which has been laid down upon a surface of low relief, either on the land or in the sea, during widespread conditions of tectonic stability in the source and depositional areas. In contrast, basin sandstone is defined as an accumulation under conditions where the site of deposition was sinking differentially, or, where sedimentation was so rapid that the deposits were buried before they could be shifted very far from the site of initial deposition. It is not the intent to designate a basin deposit as one restricted to an enclosed area, but, on the contrary, to include all deposits which because of rapid differential sinking in the site of deposition, or the piling up of sands even in a moderately stable area, develop an accumulation whose thickness may be great and whose over-all cross section is distinctly wedge-like or lenticular.

In platform deposition tectonic stability must prevail throughout the entire area of accumulation. On land such conditions would represent low surface relief, and uniformity both in climate and physiographic stages of streams, to permit the spreading of a deposit as a thin sheet. On the sea floor a broad shelf area of uniform water depth would prevail throughout the interval of deposition without differential sinking. When such conditions prevail simultaneously on land and sea, then a deposit may accumulate on land and extend out to sea as a continuous sheet of sand. To effect a complete gradation from one depositional environment to the other, steady currents must prevail so that particles within a small size frequency distribution accumulate. All material finer than the small size range settling out is swept to other sites of deposition, whereas coarse material does not enter. At no time must the supply of debris exceed the ability of the steady currents to winnow, re-work and re-distribute the sands over a broad area. In its ideal form such a sand would show a continual gradation from an area where it contains fossils of the land environment to a deposit possessing the characteristic fauna of a marine, shallow water environment; and, at its seaward terminous grade into realms of argillaceous or calcareous deposition. Certain platform sands herein called "blankets" are inferred to have been deposited under such ideal conditions (Table I).

Other platform sands are not continuous sheets or blankets. These are wedge-shaped sands which represent local exceptions to widespread deposition. They are related to irregularities either on the land, or on the sea floor,

where the local conditions diverge from that of the zone of sedimentation as a whole, and, the supply of debris differs in mineralogy and quantity. Usually such deposits are incorporated within the blankets (Table I).

TABLE I. *Characteristics of Platform Sandstones*

1. Thin, usually do not exceed 500 ft., blankets widespread, wedges local.
2. Size frequency distribution symmetrical, well sorted.
3. Cross-laminated.
4. Lack of interstitial matter.
5. Quartz enlargement common.

Basin sands accumulate in regions where there is a sudden decrease in gradient on the land, such as rivers debouching from the mountains out upon the plains, or under marine conditions where sinking exceeds the rate of heavy sedimentation. Krynine states that such deposits predominantly form during periods of orogeny as contrasted to periods of peneplanation during which certain of the platform type of sands accumulate. Basin sands are, also, both continental and marine, but deposits rarely show accumulation as a continuous gradation between the two major environments. On the contrary, basin sediments, except, for deltaic types, show evidence of being either entirely a land or entirely a marine deposit.

Whereas platform sands are characteristically cross-laminated, produced by uniform and steady currents, basin deposits show graded bedding, a structure which develops when currents rhythmically alternate in intensity. Such pulsations coupled with the abundant supply of poorly sorted debris result in size frequency distribution of material which is skewed toward the finer sizes (Tables II and III).

TABLE II. *Characteristics of Basin Sandstones*

1. Thicken abruptly into accumulating basin
2. Size frequency distribution skewed toward finer sizes, sorting poor.
3. Graded bedding.
4. Abundant interstitial material.
5. Rock fragments common as grains.

TABLE III. *Sandstone Types*

I. Platform, or uniform current-sorted sandstone types
A. Blankets
1. Pure quartz
2. Quartz-glauconite
3. Quartz-muscovite
4. Quartz-iron oxide
B. Wedge or lens-shaped
1. Quartz-potash feldspar
2. Arkose
II. Basin, or rhythmic current-sorted sandstone types
A. Arkose
B. Graywacke
1. Littoral
2. Fluviatile or deltaic
3. Neritic

PLATFORM SANDSTONES

Sandstones called platform deposits, and which show the characteristics listed in Table I, have been subdivided into several more or less distinct types named after their dominant mineralogic constitution but classified to a large degree on the basis of other characteristics many of which reflect the environment of deposition.

Pure Quartz Type. Sandstones classified as pure quartz type are the most distinct of all the platform deposits. Formations such as the St. Peter (11), Sylvania (8), Tensleep (7), Coconino (33), Dakota (35), and Simpson (13), are representatives. These show certain over-all characteristics which link them together as follows:

1. They are widespread blankets of sand commonly covering an area of several states. Despite their wide areal extent they are thin, usually less than 500 feet.

2. They have been deposited uncomformably upon the underlying beds, often upon an irregular surface. Such a rela-

tionship is suggestive of rapid encroachment of the land by the sea.

3. Cross-lamination is prominent and commonly shows eolian and aqueous types at different localities. An example would be where a sheet of sand was accumulating as dunes along a shore and extending seaward as a marine deposit. In both environments the steady current typical of platform deposition could cross-laminate the accumulating sand.

4. Sorting is excellent, and size frequency distribution curves typically show that 68% of the grains (one standard deviation) are included within one phi unit of Krumbein.

5. The mineralogy is extremely simple, 95 per cent of the grains being clear quartz. Such grains show "frosting," pitting, and prominent quartz enlargement on grains which were formerly highly spherical.

6. Cementation of the particles is commonly poor although this is not always the case since certain quartzites belong to this type. The cementing material is generally silica, sometimes as crystalline quartz but also as chalcedony. Dolomite is not an uncommon cement, particularly in the seaward portions where the deposit is grading into the quartz-glauconite type.

7. Heavy minerals are usually few in quantity, not uncommonly constituting 1–2 per cent of the rock. Moreover, these minerals represent a very stable suite and are chiefly leucoxene, tourmaline, staurolite, limonite, and magnetite listed in general order of abundance.

8. Fossils are rare and are usually restricted to worm borings, plant fragments, lamellibranchs, and brachiopods.

9. Commonly this type appears to have been deposited on the land as dunes which extend into the shallow water marine environment as a continuous sheet. Seaward such sands may grade into the quartz-glauconite type, where normal marine conditions prevail; or into the quartz-iron oxide type where evaporites are accumulating.

Quartz-glauconite type. These sandstones are representative of somewhat deeper water marine equivalents of the pure quartz type and in consequence show less variation in characteristics. The Cambrian sandstones of Wisconsin, the Sundance, and the Tombigbee sandstone (Eutaw formation), are typical. They show, in addition to the general characteristics of the platform sandstones, other features as follows:

1. Aqueous cross-lamination, ripple mark, and mud crack.

2. Very good sorting, the size frequency distribution curves show that 68 per cent of the grains are included within one phi unit. Generally the modal grain size is smaller than the pure quartz type.

3. 90 per cent of the grains are clear quartz, the remainder are chiefly glauconite but may also be dolomite, calcite muscovite, and chert. The chert, sometimes of granule or pebble size, is rather common near the base. Grains range from angular to well rounded and spherical. Frosting, pitting, and quartz enlargement is prominent.

4. Cementation is generally poor and the chief cements are quartz, chalcedony or dolomite.

5. Heavy minerals are few in quantity, representative of a stable suite, and are commonly leucoxene, zircon, tourmaline, rutile, chlorite, epidote, garnet, kyanite, ilmenite, and staurolite.

6. Fossils are marine shallow water forms, brachiopods, pelecypods, worms, and, in Paleozoic rocks trilobites.

7. Shoreward this type grades into the pure quartz sands, whereas, seaward, the sandstone grades into sandy dolomite and dolomites. The presence of glauconite suggests slow deposition.

Quartz-iron oxide type. Quartz-iron oxide sandstones are those associated with typical red-beds. The Chugwater, Maroon, Wingate, Abo, and Lake Superior sandstones are examples. They are similar to the pure quartz type in that they show features of having been deposited as continuous sheets extending from the continental into the marine environment. Here the high oxidation po-

tentials present on the land were maintained, and the iron remained in the ferric state. Gradations into, and associations with, the pure quartz type are noteworthy. These suggest environments of deposition which must differ chiefly in the existence of evaporite pans and the supply of ferric oxide when the quartz-iron oxide type develops. Platform arkoses also frequently form an integral part of quartz-iron oxide sandstones, and all gradations are found between those in which potash feldspar is absent to those classified as true arkoses. Specific characteristics of quartz-iron oxide sandstone follow:

1. They occur as widespread blankets which repeatedly occur separated by intervals of shale and siltstone; hence, the total may appear thick (1000 ft.±).

2. Cross-lamination is prominent and both aqueous and eolian types are recognized in the same formation. Rain drop imprint and mud crack attest to depositions at least in part, in a subaerial environment.

3. Sorting is moderately good with 68 per cent of the grains concentrated into 2 phi sizes. Nevertheless, a wide range in modal grain size prevails between localities.

4. The rock consists largely (90% ±) of well rounded or nearly spherical grains of quartz coated with iron oxide. These may show quartz enlargement but if so it is seldom more than minor. Normally the quantity of potash feldspar is low but may increase into that appropriate for arkoses (25 per cent).

5. The cements are chiefly iron oxide and silica, but, gypsum and calcite are known.

6. Heavy minerals are stable, few in species and number. Tourmaline, zircon, magnetite, ilmenite, and garnet listed approximately in their order of abundance are most frequently reported.

7. Fossils are generally continental vertebrates, and plants, often well preserved; whereas, the marine sections are sparingly fossiliferous but do contain brachiopods and pelecypods.

Quartz-potash feldspar type. These sandstones are gradational between the pure quartz, quartz-muscovite and arkose types; hence they constitute a class whose limits are arbitrarily defined. Such sand accumulations are derived wholly or in part from a granitic terrain which furnishes the feldspar in quantities sufficient to make it a prominent constituent. Normally they are not widespread formations but occur as local developments in one of the aforementioned types. They are commonly deposited in the littoral and near shore marine environment where plant fragments are incorporated with the remains of marine organisms which inhabit such zones. Sandstones in the lower Mesaverde of central Colorado are representative. Certain special characteristics follow:

1. They are local, lens or wedge-shaped and generally less than 100 feet thick.

2. They commonly lie unconformably upon the underlying strata.

3. Aqueous cross-lamination is often present.

4. Sorting is moderate to poor but interstitial clay or silt forms only a small part of rock. Some deposits are coarse sands whereas others are very fine sands.

5. Quartz fragments usually are clear, angular, or sub-round and constitute approximately 75 per cent of the sample. Potash feldspar is present in quantities less than 25 per cent, and some mica occurs chiefly as interstitial matter.

Quartz-muscovite type. Sandstones of this type are typical of the Pennsylvanian of the Appalachian Plateau, the Derry Series (Pennsylvanian) of New Mexico, some of the channel sandstones of the Pennsylvanian of the Central Interior Coal Basin, and the upper part of the Mesaverde of Central Colorado. These are sediments which appear to have accumulated chiefly in an environment associated with large alluviating rivers emptying into regions of extensive tidal flats. Ordinarily they are more restricted areally and thinner than other platform deposits. Moreover, deposition has not been entirely in an environment of steady,

uniform currents, and in consequence a greater percentage of interstitial fines are present.

1. They generally lie unconformably upon the underlying strata. Such unconformable relationships may be local "cut and fill" structures characteristic of alluviating streams or they may be more areally continuous and involve minor diastrophic movements.

2. Aqueous cross-bedding, particularly in the very coarse sandstones, is commonly "torrential" with foreset beds 2 to 3 feet in height.

3. Sorting is moderately good within an individual deposit, 68 per cent of the grains occurring within 2 phi units; but between deposits a wide range of grain size obtains so that virtually all grade sizes are recognized between conglomerates and silts. Within the sandstone unit normally the grain size decreases upward and the bedding becomes thinner and flaggy.

4. Quartz is the most common mineral (10% ±), and usually occurs as clear, or iron-oxide stained, subangular, or angular grains. Muscovite, sometimes in flakes of 2 mm. in greatest diameter, occurs in quantities from 10–30 per cent, and is generally distributed along, and parallel with, the bedding. Biotite in minor quantities is the only other prominent mineral.

5. Quartz enlargement is recognizable but not prominent.

6. The cementing material is generally silica and less commonly calcite or dolomite. Locally, however, these may be sufficiently prominent to produce a granular calcareous sandstone.

7. Heavy mineral suites show a greater number of mineral species than the pure quartz and quartz-glauconite types, and an increase in the number of moderately stable varieties. Leucoxene, tourmaline, sphene, ilmenite, magnetite, rutile, zircon, garnet, and traces of amphiboles and pyroxenes, listed in order of abundance, are the usual occurring minerals.

8. Quartz pebble conglomerates are sometimes present at the base.

9. Fossils are well preserved plant fragments which apparently have undergone only minor transportation. Coal as fragments and thin $\frac{1}{2}''$–$\frac{1}{4}''$ streaks is also common.

6. Silica forms the principle cement and ordinarily the cementation is poor.

7. The heavy minerals contain more unstable varieties than most platform types and amphibole, pyroxene, biotite (often bleached), ilmenite, zircon, epidote, and spinel are representative. In certain instances the unstable varieties may predominate in abundance.

8. Fossils associated with quartz-potash feldspar sands are plant fragments, and shallow water marine forms (brachiopods and pelecypods).

Platform arkose type. Arkoses of this type commonly appear associated with quartz-iron oxide or pure quartz sandstones but they also are associated with the quartz-potash feldspar and quartz-muscovite types. Apparently arkoses form as a platform deposit where some local granitic terrain is sufficiently elevated to furnish arkosic material as a local deposit adjacent to the source area. In consequence they seem to be associated with a variety of environmental conditions sometimes terrestial and sometimes as shallow water marine deposits. Platform arkoses have the following general characteristics:

1. They are thin, generally less than 100 feet, lens or wedge-shaped, local and sporadic in distribution.

2. Commonly they lie with disconformable relationships on the underlying strata.

3. Aqueous cross-lamination, often of a "torrential" type, is frequently seen in the marine deposits.

4. Sorting is moderate and estimated to have a standard deviation of about 3 phi units. More data are required to further clarify the general size frequency distribution of such material, and in view of the variety of environments in which it occurs it is reasonable to expect a wide range in the standard deviation.

5. Potash feldspar commonly in grains coarser than 2 mm. constitutes 25–60 per

cent of the rock, and interstitial clays are low.

6. Ordinarily the cement is silica but calcareous cement occurs. Cementation is generally poor.

Basin Sandstones

Basin sandstones are catalogued under two main groups, arkoses and graywackes (Table III). The writer expects this grouping to undergo considerable modification as basin sandstone types become more clearly defined but at present the proposed groups appear to satisfy most of the data on hand.

Basin arkoses. Basin arkoses differ from the platform arkoses primarily in their thickness and quantity of interstitial matter but they also have characteristics which associate them more with fluviatile than near shore marine deposits. They grade into coals, shales with rain drop imprints, footprints of land animals, contain plants commonly well preserved, and suggest a flood of uncompletely weathered granitic material into an accumulating basin. Krynine suggests that deposits of this type are the result of ultra-rapid erosion on steep slopes in a tropical humid climate. Arkoses of the Triassic of New Jersey and Carboniferous of the Narragansett Basin are typical (3). Such deposits show the following characteristics:

1. They are lens or wedge-shaped, and reach thicknesses of the order of 500 feet.
2. Graded bedding is prominent in layers 1 to 2 feet thick.
3. Sorting is poor with much fine material, generally interstitial, hence the size frequency distribution is skewed toward the fine sizes.
4. Potash feldspar constitutes less than 50 per cent of the larger fragments, whereas plagioclase, quartz, muscovite, biotite and rock fragments (granite, shale, and limestone) form the remainder. Interstitial matter consists of clay minerals and comminuted quartz, muscovite, chlorite, and feldspar.
5. Carbonate cements are common.
6. The heavy minerals suite is large, varied, and consists predominantly of unstable minerals such as biotite, pyroxene, amphibole. Others such as magnetite and zircon are common.

Graywacke

Graywackes are the typical basin sands just as the pure quartz blankets are the typical platform deposits. They possess the green-gray color, the graded bedding, and comminuted rock fragments commonly associated with rapid accumulation. Sediments of this type are associated with near shore marine and fluviatile deposition where bars, deltas, sudden alternations from agitated to quiet waters, and a heavy supply of debris prevail. Where such conditions grade into a deeper water environment, currents are subject to pulsations of smaller intensity ranges, sedimentation proceeds at a diminished rate, glauconite forms, and marine organisms are preserved in abundance. Certain characteristics are common to the graywackes namely :

1. They accumulate as lens or wedge-shaped deposits as much as 2000 feet thick.
2. Graded bedding is a very prominent feature and is usually developed in layers not exceeding a foot.
3. Rocks of this type have a smaller modal size than arkoses. They are typically poorly sorted, and fine material is more abundant than coarse, so that the size frequency distribution is skewed toward the smaller sizes.
4. Commonly 50% ± of the mineral composition is quartz, often stained; whereas, chert 20% ±; rock fragments (quartzite, schist, slate, and shale) 10% ±; feldspar (Plagioclase dominant). 5% ±; and interstitial clay 15% ±; are represented in the indicated proportions.
5. Silica as a cementing material most frequently occurs but dolomite and also siderite are common.
6. Pyrite is always present as a heavy mineral, but amphibole, rutile, biotite, magnetite, epidote, zircon, ilmenite, and tourmaline are present often in quantities in the order of listing above.

Over and above the general characteristics listed certain special features appear which are developed in the environment of deposition. Certain graywackes such as the Bartlesville and Bradford "sands" are elongate lenses in a shale unit. Such sandstone lenses have a lineal orientation suggestive of deposition as barrier beaches (5, 14). If such is their origin they are representative of graywackes deposited in the littoral environment.

Another graywacke type occurs as channel fills, contains shale pebble conglomerates, well preserved pelecypods, gastropods, and plant remains. These are considered to have been deposited in broad flood plains near the mouths of streams or as deltas and, hence, are classified as fluviatile or deltaic graywackes. The central part of the Mesaverde formation in Colorado, and the Wasatch and Green River formations in Wyoming show such characteristics.

A third type of graywacke represented by sandstones of the Frontier, Eagle, and Cody formations contains abundant chert and glauconite, primary calcite or dolomite, and, is commonly tuffaceous. Associated with the graywacke mass are thin lenses of brown or gray, dense, siliceous sandstones often with fucoidal markings on bedding plane surfaces. Organisms are abundant and are dominantly pelecypods, brachiopods and cephalopods, usually occurring in lenticular zones in the finer grained portions of the rocks. From such characteristics a shallow water marine environment of deposition is inferred, and hence, they are classified as neritic graywackes.

CONCLUDING REMARKS

Except for the arkoses, sandstones of the platform type are sufficiently distinct to permit classification into groups whose characteristics are clearly defined. Moreover, because of the stable tectonic conditions prevalent during such deposition their characteristic features show little change over broad areas. Basin deposits, however, accumulate under conditions of greater variability and mild or intense orogeny; hence, uniformity in minor characteristics is not to be expected. Furthermore, Krumbein* has suggested that when basins become filled and subsidence ceases temporarily, conditions suitable for platform sedimentation prevail. Therefore, platform deposits may mark the close of basin sedimentation, or, if tectonic activity is again resumed, such deposits may lie between those of typical basin accumulation.

Subdivisions of the graywackes and interpretation of the environmental conditions under which they have accumulated is particularly complex. Graywackes associated with active orogeny within the geosynclines are apt to differ from those accumulating in basins subject only to downwarping. In the proposed classification the writer has avoided this issue since the effect of metamorphism penecontemporaneous with deposition must first be evaluated. When such information is assembled the graywacke types can be more precisely delimited.

The writer has intended this communication chiefly to direct the reader's attention toward organizing sedimentary types in keeping with the present regional stratigraphic concepts. Hence, this paper is presented as an exploratory venture in the interpretation of sandstones in terms of these concepts.

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* Personal Communication.

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SHALES AND THEIR ENVIRONMENTAL SIGNIFICANCE*

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ABSTRACT

Shales can be divided into several groups on the basis of their areal extent, uniformity or variability of lithologic properties, and lithologic associations. It is believed that the broader environmental features of shales can be reconstructed from areal patterns of their lithologic and faunal attributes, but the detailed environmental analysis of single samples must await further research on clay minerals and on conditions of deposition of modern muds. A sedimentary-tectonic grouping of shales is suggested as a basis for classification; and a rapid routine of shale examination is described which affords data for areal mapping.

INTRODUCTION

The term shale is applied to a wide variety of rocks, ranging from consolidated clay and silt to rocks which display thin bedding without regard primarily to texture or composition. The writer follows Twenhofel in defining shale as the indurated equivalent of silts and clays. The cleavage is that of bedding, which is generally in thin units. Shale includes siltstone and claystone; the former is indurated silt and the latter is indurated clay. The term clay is used in a textural sense, and refers to the size of the non-calcareous particles. If the mean grain size lies between 0.062 and 0.004 mm. the rock is a siltstone, and if finer than 0.004 mm. it is a claystone. This terminology permits flexibility in describing particular rocks as sandy siltstones, silty claystones, etc., depending upon the mean size and the proportions of the qualifying materials

As a group the shales probably have been least critically studied of the sedimentary rocks, because of the difficulty of recognizing the finer mineral grains under the microscope, the difficulty of obtaining complete mechanical analyses, and the large element of post-depositional change. Yet the shales comprise by far the larger part of the sedimentary lithologic column, and are so varied in color, textures, mineralogical composition, and types of fossils, that they should be excellent indices of environmental conditions if the relations between their characteristics and the environment could be demonstrated.

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PROPERTIES OF SHALES

Complete textural analyses of shales are relatively scarce in the literature, both because of the difficulty of dispersing the rocks and the difficulty of determining sizes below 1 micron. Among examples available to the writer, shales in general show moderate to poor sorting, with from 3.5 to 5 Wentworth grades in the central portion of the distribution (phi sigma of the order of 1.8 to 2.5). Most shales are skewed toward the finer sizes, but occasionally a shale is found which tends toward a normal curve. Miss Gripenberg, some years ago, suggested that skewed curves are characteristic of fine-grained sediments, and there is some hydrodynamic evidence in favor of such an hypothesis. From the standpoint of environmental analysis the mean size and other size characteristics are useful for indicating the order of magnitude of currents and possibly the degree of turbulence. Complexities enter, however,

because, in general, it is not known whether the finer particles are carried as individuals or as flocculated aggregates.

The mineralogical analysis of shales is hindered by the small size of the particles and by the difficulty of identifying the clay fraction completely. Grim investigated the relation of clay minerals and other constituents to the size frequency distribution of weathered materials, and emphasized the need for a knowledge not only of the clay minerals present in shales but of the relative abundance of the several varieties.* Studies of the clay minerals should supply information necessary to state the conditions under which the source material was weathered, and the nature of the post-depositional environment. Minerals in the coarser silt fractions of shale can be readily identified, and they include quartz, orthoclase, plagioclase, muscovite, pyrite, gypsum, chlorite, etc., some of which are relatively abundant. Typical associations occur in some shales, but in general there is considerable overlap among the mineral suites.

Chemical analyses of shales are difficult and time consuming, and many published analyses are incomplete. Aluminous, siliceous, and calcareous types occur, but a number of shales are of mixed types, and further study of the subject is needed. Cummings and Shrock used chemical analyses to show the areal variation of the Missinissewa shale in terms of its argillaceous and calcareous content, as an index to the direction of movement of detrital material. Trask and Patnode have published many analyses of the organic content of shales, and their report includes a number of maps showing the regional variation of organic content and other shale attributes.

Structures associated with shales, especially mudcracks, raindrop impressions, and the like, are indicative of some environmental conditions. Shale bedding varies from paper-thin to relatively massive; Payne has suggested a classification of bedding into four types (fissile, shaly, flaggy, and massive) depending upon the thickness. The first two groups in his classification could be further subdivided for shale purposes. The exact significance of bedding in shales is not known, but it appears to be related to the quietness of the sea bottom during or immediately after deposition. Rhythmic bedding in shale has received much discussion, and Bramlette recently examined the question in connection with the diatomaceous shales of California.

A conspicuous attribute of shales is color, upon which much reliance has been placed as an index of broad environmental conditions. The critical study of black shales by Twenhofel has shown, however, that there are limitations to the specific environmental interpretations which can be made from color alone. It is likely that a similar analysis of red shales would show both marine and nonmarine equivalents, as well as shallow and deep-water varieties. The red color of some marine shales is apparently an index of the absence of reducing conditions (controlled in part by the lack of abundant organic material) which permit the red color of the source material to remain in the final deposit. Gray, brown, and green shales undoubtedly also show a wide variety of conditions of formation.

The fossils contained in shale, providing they represent forms which inhabited the site of preservation, are perhaps the most critical indices of environmental conditions. Among Paleozoic marine shales the more argillaceous varieties have typical molluscan faunas, which grade into brachiopod-bryozoa assemblages as the calcareous content of the shale increases. Brackish environments tend toward *Lingula*, *Mya*, and *Mytilus* assemblages; and terrestrial assemblages contain leaves, plant fragments, footprints, and so on. Data are available on the specialized faunas in black shales and in some other particular types, which

* Oral discussions at the Los Angeles meetings of the A.A.P.G. Research Committee and at the S.E.P.M. symposium.

have a strong bearing on environmental interpretation. As far as the writer is aware, however, relatively little has been done on the quantitative paleoecological aspects of the broader shale groups.

CLASSIFICATION OF SHALES

The preceding discussion indicates that organized quantitative knowledge about shales is not abundant. Much can be done with combinations of data, as Rubey showed in his study of Upper Cretaceous shales in Wyoming, and the implication is that many environmental problems will be clarified as organized data accumulates. The broader environmental aspects of shales can be reconstructed even without critical quantitative data, but it is believed that detailed knowledge of specific environmental factors such as water depth, strength of currents, and others, can come only from additional fundamental research on textures, mineral assemblages, the significance of clay minerals, and paleoecological relations.

In the absence of sufficient critical data to set up a genetic classification of shales based on environments, a more descriptive classification is appropriate. The descriptive data are related to environmental conditions in part, so that a descriptive grouping can be maintained sufficiently flexible for modification as genetic data accumulate. There are several bases for classifying shales, and these are summarized in the following outline:

Descriptive Classifications of Shale

Color

- White, cream, light gray to brown
- Green to blue
- Red, maroon, purple
- Dark gray to black

Texture

- Sandy siltstones
- Siltstones
- Clayey siltstones
- Silty claystones
- Claystones
- Sandy claystones

Mineralogical Composition

- Type of clay mineral
  - Kaolinite
  - Montmorillonite
  - Illite
  - Combinations
- Associated "silt" minerals
  - Quartz
  - Orthoclase
  - Plagioclase
  - Calcite
  - Muscovite
  - Chlorite
  - Gypsum
  - Pyrite

Chemical Composition

- Aluminous
- Siliceous
- Calcareous
- Carbonaceous
  - Humic
  - Bituminous
- Ferruginous
- Phosphatic
- Etc.

Structures

- Thickness of bedding
- Rhythmic bedding
- Associated concretions

Fossils

- Marine assemblages
- Brackish to fresh-water assemblages
- Terrestrial assemblages
- Dwarfed, depauperate, and other aberrant assemblages.

The examination of numerous shale samples ranging in age from Cambrian to Tertiary, collected from a number of localities, showed that on any of the preceding bases of classification (color, texture, etc.) there is almost complete overlap of the subdivisions. That is, under a main particle size classification, each textural group includes all the color groups, each color group includes most of the compositional groups, and so on. This implies that given combinations of shale characteristics may be developed under varying environmental conditions,

and that a given environment may produce shales of varying characteristics. It is doubtful whether a classification of shale directed toward a single sample can unequivocally demonstrate the genesis of the shale, at least in the present state of knowledge.

In order to develop a more fundamental basis of shale classification, some of the larger areal characteristics of shales must be considered, such as the thickness of the shale body and its lateral thickness changes; the widespread or local occurrence of the shale; its lithological uniformity or variability; and its associated lithologies. These larger features of the shale are related to the broad environmental conditions of the deposit and to the tectonic control of the sedimentation. Studies of sedimentary tectonics by Jones, Bailey, Krynine, Pettijohn, Tercier, and others have shown that lithologic properties and associations are related to geosynclinal or platform conditions, but the phenomena are complicated by the occurrence of a variety of geosynclinal conditions. Kay has described a number of geosynclinal types, which include such diverse features as the autogeosynclinal Michigan Basin and the larger orthogeosynclines of the Appalachian district. The lithofacies of the Michigan basin more nearly resembles platform deposits than eugeosynclinal deposits, although there is marked thickening of numerous stratigraphic intervals in the Michigan Basin. Intracratonic basins especially may display intervals of crustal stability during which they behave as normal platform areas without marked thickening of their deposits. During such times the lithofacies would be normal platform types.

Despite the difficulties involved in setting up sharp classifications of lithofacies related to environments controlled by geosynclincal or platform conditions, there is no doubt that the tectonic framework provides a broad basis for the interpretation of ancient sediments. The study of these larger features of shales is essentially a mapping problem, and it shifts emphasis from the interpretation of a single sample to a spread of samples over an area. The broader features of the environment can be reconstructed by mapping variations in the shale and studying the resulting areal patterns in terms of the magnitude and rate of change of the shale characteristics. A number of characteristics may be used for these mapping purposes, and in a later section a routine of rapid shale examination is suggested.

In view of the state of flux in current thinking about the relations among environments, sedimentary facies, and tectonic controls, any proposed classification of shales must be tentative and flexible. The broad grouping suggested below is based primarily on areal relations; and emphasis is placed on the magnitude and rates of change of shale characteristics in the entire shale body, considered as a sheet of sediment which may have accumulated under conditions of several enrivonments. For example, broad sheets of shale may extend from terrestrial (alluvial) phases through marginal shore phases, and into true marine phases. In detail several environments may be involved, and yet the entire spread of environments may occur on a stable platform area. It is believed that the evidence may be obtained both for the broader tectonic framework of the sedimentation and for the sequence of environments by mapping the attributes of the shale over as much of its extent as is available for study. By using numerical data as far as possible, contour type maps may be prepared which show the changes and their rates by means of isoliths, which are lines of equal lithologic character. Areas in which the isoliths are crowded together will suggest transitions in environmental or tectonic conditions, and focus attention on smaller areas in which detailed studies may be made. Close spacing of isoliths may also show linear or other trends, which may suggest littoral or other significant environmental conditions. Isopach maps of the shale interval, used in conjunction with isolith maps, furnish important data on the location and extent of platform and basin facies.

TECTONIC AND ENVIRONMENTAL CLASSIFICATION OF SHALES

I. *Uniform thickness and lithology* ("*Platform type*")

A. Widespread stable platform, no strong positive areas.

Characteristics often remarkably uniform over large areas, with transitional rather than abrupt lithologic changes.

Gray, green, brown, black; red less common.

Sandy siltstones to claystones; finer textures predominate.

Abundant rounded quartz in silt sizes; feldspar not common; shale may be calcareous, glauconitic, carbonaceous.

Associated with quartzose sandstones, clean cherty limestones and dolomites.

Inferred environmental conditions are broad shallow seas or wide alluvial plains, with fossils a guide to local conditions; textures related to energy of transporting media; color a function of source materials, organic content, and post-depositional conditions. Conventional environments include terrestrial plains, marginal lagoonal areas, shallow open seas. Black shales may indicate restricted circulation or fairly rapid deposition.

B. Fairly stable platform associated with unstable source areas.

Characteristics may be fairly uniform regionally, but with abrupt local changes.

Gray, green, red, chocolate

Sandy siltstones to claystones; coarser textures predominate.

Variety of minerals in silt sizes, with feldspar sometimes prominent; shale may be micaceous, carbonaceous, less commonly calcareous.

Associated mainly with arkosic sandstones, nodular limestones.

Inferred environmental conditions similar to (IA) above, but possibly with greater tectonic activity in source area. The shales are likely to have smaller areal extent than (IA), and the gradations into other facies may be more rapid and irregular locally.

II. *Variable thickness and lithology* ("*Basin type*")

A. Relatively shallow intracratonic basins; source areas mildly positive or relatively remote.

Thicknesses and lithologic characters may show abrupt changes or transitions; regional changes more pronounced than in group I.

Gray, green, red, brown, black

Sandy siltstones to claystones; coarser textures common.

Variety of minerals in silt sizes; grains usually subangular; mica often abundant; shale may be calcareous, siliceous, carbonaceous.

Associated sandstones range from low to relatively high in interstitial material; associated limestones range from clean varieties to argillaceous types. Special associations may include evaporite sequences.

Inferred environmental conditions are shallow seas or marginal areas in and adjacent to basins which sink as sedimentation advances. Shale textures and composition reflect adjacent contemporary positive source areas. Inferences from color as in group (I). Conventional environments include alluvial plains, deltaic conditions, marginal lagoonal areas, and open or restricted marine conditions. Black shales and evaporite sequences indicate restricted physical or chemical conditions, toward close of sedimentary cycle.

B. Tectonically active marginal geosynclines with strong positive source areas.

Thickness and lithologic characters usually show abrupt variations, but specific members may show transitions.

Gray, green, red, brown, black

Sandy siltstones abundant; finer textures less common.

Large variety of minerals in silt sizes, including highly unstable types; grains usually angular. Chloritic material usually abundant; shales may be siliceous, micaceous, calcareous, carbonaceous, pyritic.

Associated with graywacke sandstones (arkosic associations here more indicative of marginal aspects of IIA); limestones usually siliceous, dense, dark.

Inferred environmental conditions include

a range from terrestrial to marine with rapid deposition a conspicuous element. Shale textures and composition indicate poor sorting and relative nearness to strong positive areas. Black shales probably are more a function of rapid deposition than of restricted circulation. Rapidity of textural and other changes suggest unstable environmental conditions.

The preceding classification shows considerable overlap among the conventional environments which occur under the main classifications. This is inevitable inasmuch as shorelines or alluvial plains may be present under a variety of tectonic conditions. It is believed, however, that the areal pattern and the vertical lithologic associations of the several environmental types will be different under varying conditions of stability or instability. Shores along unstable areas may show more rapid horizontal and vertical variations of properties, whereas along stable shorelines there may be greater opportunity to reach equilibrium conditions. Contemporaneous structural deformation has become so large a part of subsurface thinking that it is desirable to attempt some integration of the environments, their lithological expression, the tectonic framework, and the type of basin in which deposition occurred. It is anticipated that as data accumulate there will be marked changes in shale and other lithological classifications, with emphasis shifting to the complete mapping of correlative intervals regardless of whether the interval is a single lithology or grades from one kind of rock to another. By such broader approach a more complete environmental and tectonic picture will result, but for present purposes it is important that the regional environmental features of shales be understood so that extrapolations of the data may be made toward shorelines or other areas of interest.

The writer is of the opinion that no satisfactory shale classification can be developed until maps are available which indicate the range of conditions and the types of patterns which occur. Trask and Patnode include a number of regional maps of shales which carry many suggestions for further study, and which illustrate a number of broad regional patterns. Which of the mappable characteristics of shales will prove most significant in environmental studies probably cannot be predicted, but the writer has assumed that the larger features of the shale body, the rates of change of its characteristics, its mineral composition, and its lithologic associations vertically and laterally, will prove to be fundamental. The suggested classification is based on these elements, and is subject to modification as mapped data accumulate.

The arkosic associations appear to be particularly troublesome, inasmuch as they occur in both platform and basin associations. Dapples has pointed this out in his analysis of sandstones, and the writer groups these associations with his platform types (Group I-B), although they also occur in the marginal phases of strong basins (Group II, A and B). Similarly, the transitions of lithologic types from platform to basin facies in limestone is pointed out by Sloss.

ROUTINE OF SHALE EXAMINATION

The difficult and time-consuming nature of detailed shale analysis suggests that some rapid method of deriving mappable data from shales will provide a means for implementing the suggested tectonic and environmental classification. The writer has experimented with various routines of examination, and the following method has the merit that it provides semi-quantitative or relative numerical data which can be made the basis of isolith lines on lithofacies maps. The rapid examination should be supplemented with more detailed textural, mineralogical, chemical, and faunal data where possible, in order to tighten the control points on the map.

The routine is mainly designed for cuttings, although outcrop samples may be crushed and examined in the same manner. The equipment includes a binocular microscope, about 12 to 16 power, a set

of watchglasses, dilute hydrochloric acid, concentrated sodium hydroxide solution, and a set of visual standards for comparison, which are described below. A number of typical cuttings is first examined in a wet or dry state for gross properties (color, bedding, over-all texture); and part or all of the same cuttings are crushed for further analysis. Two portions of the crushed cuttings are placed on watchglasses; one sample is treated with acid and the other with alkali. The acid reaction is watched under the binoculars until it is completed, using hot acid if necessary, and then the sample which has been soaking in the alkali is studied, using a stiff brush or muddler to break down the shale aggregates. The amount of clay and its rate of breakdown are estimated. The material in both watchglasses is then washed by decantation and the sand and silt content is examined for texture, mineral composition, and the presence of fossils. The observational data are tabulated as shown in Table 1. The routine as described requires about 15 minutes per sample, but this time can be reduced on a systematic schedule.

TABLE 1. *Example of Shale Sample Examination*

Name and Locality: Francis Creek Shale (Pennsylvanian, Fulton County, Illinois)
Color: Medium greenish gray
Bedding: Thin, irregular
Over-all Texture: Coarse, uneven
Effervescence: None
Sand and silt grains
Proportion of sample: 60 per cent
Relative mineral abundance
Quartz +++
Feldspar +
Muscovite+++
Pyrite rare
Textures
Average size 0.05 mm.
Sorting (σ_ϕ) 2.0
Roundness 0.3
Sphericity 0.8
Fossils: None; few carbonaceous flakes
Tentative Inferences: Shallow water, possibly marine; moderate distance from shore; source area not remote; mainly a first generation sediment in group IB or IIA of the shale classification.

The set of visual standards used in the examination includes a scale for estimating degrees of effervescence, such as that proposed by Maddox, and a set of standards for estimating the textures of the sand and silt grains. These consist of scatterings of grains in microfossil mounting slides, each cell of which contains particles of a given average size or degree of sorting; and sets of drawings for estimating roundness and sphericity (Krumbein; Rittenhouse). Color standards were not developed, although it may be desirable to prepare a set from typical shales.

In mapping the sample data they may first be averaged over the interval used, or the vertical variations in each well may be shown on a graphic log. Qualitative maps may be made of the color, the over-all texture, the kind of bedding, and the nature or abundance of fossils. On such maps lines may be drawn between main classes, as between greenish and bluish shales in contrast to reddish and brownish shales. Other data are mapped more quantitatively: the sample in Table 1 lies along the zero line of lime content; it lies in an area of abundant mica content; and the size, sorting, roundness, and sphericity afford data for isolith lines. An isopach map of the shale interval is also very useful.

The routine for rapid shale examination is not proposed as a substitute for more detailed work; after the regional picture is obtained it is desirable to study critical areas in more detail. Payne's method of study proves very useful in such work. In addition, the fossils present deserve consideration in terms of types, relative abundance, and other aspects, but the writer is not qualified to develop methods for this purpose.

CONCLUDING REMARKS

The growing importance of the environmental and contemporaneous structural significance of shales and other sedimentary rocks in subsurface exploration and in paleogeographic studies points to the need for systematic methods of organizing the large body of data already available. This shift in emphasis

to a spread of data places the individual sample within its proper environmental and tectonic framework. Where it is necessary to make interpretations from a single well, the vertical associations of the shale are of value in setting the sample into this framework and thereby suggesting the broader conditions of deposition.

The present paper is an attempt to integrate environmental concepts, the sedimentary-tectonic viewpoint, and the regional-stratigraphic grouping of basins and geosynclines, building on the work of Twenhofel and others on environments; on Jones, Krynine, Pettijohn, and others on sedimentary tectonics; and on Kay and Stille on the classification and characteristics of geosynclines. Each of these bears on the central problem of interpreting the rock column, but the relative importance of each in given rock associations needs further clarification.

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ENVIRONMENTS OF LIMESTONE DEPOSITION

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ABSTRACT

Limestones may be divided on the basis of their depositional environments into three categories: 1) platform, 2) basin, 3) geosynclinal. Platform limestones are thin, widespread, light colored, fossiliferous limestones which are often dolomitized. Basin limestones of the open basin type are lithologically similar to platform limestones, but display differential thickening. Barred basin limestones are typically the first stage in depositional cycles which include primary dolomites and evaporites. Basin margins are commonly marked by linear zones of reef limestones. Geosynclinal limestones deposited under shallow-water conditions are lithologically similar to platform limestones, but display great differential thickening in linear belts. Deep-water geosynclinal limestones are black, dense in texture, and siliceous.

Emphasis is placed on the principle that understanding of depositional environments requires three dimensional mapping of sedimentary attributes over large areas, plus detailed study of lithologic associations.

INTRODUCTION

The preceding papers by Krumbein and Dapples propose classifications of shales and sandstones in terms of the tectonics of their depositional environments and source areas. This brief note represents an attempt to orient carbonate sediments within the framework of the classification proposed for medium and fine grained clastics.

A classification of carbonates based solely on tectonic control must be lamentably incomplete. Carbonates normally accumulate under conditions of crustal stability and are far more sensitive to the chemistry and organic population of the waters from which they are deposited than to the tectonics of their environment. Moreover, carbonates are subject to a wide variety of diagenetic and other post-depositional effects which, more often than not, serve to obscure the original primary nature of the sediment. Nevertheless, there is an apparent correlation between the lithologic and biologic characteristics of limestones and their tectonic environment. Division into recognizable types is much less simple than in the case of sands, and occurrence of types beyond the limits of their supposed typical environments is, perhaps, more the rule than the exception; however, a certain order prevails in limestone associations, and a classification is proposed herein.

LITHOLOGIC DESCRIPTION AND CLASSIFICATION OF CARBOHYDRATES

Development of a systematic nomenclature for the description of carbonate textures, colors, and structures is one of the current projects of the Research Committee of the A.A.P.G. Until the Committee's report is made and accepted carbonates will continue to be described in terms that are intelligible only to the geologist making each description and, possibly, to his immediate colleagues. In order to avoid further confusion the short glossary below defines the usage of this writer for certain textural terms:

Fragmental—composed in large part of fossil fragments, commonly crinoid columnals.

Crystalline—composed of coarse crystals without obvious organic structures; often the result of dolomitization of fragmental limestones.

Saccharoidal—an academic euphemism for "sugary."

Dense—aphanitic, with conchoidal fracture and normally unfossiliferous or nearly so.

Normal marine—lacking any special textures such as those above; moderately fine-grained and moderately fossiliferous.

PLATFORM LIMESTONES

Platform limestones are deposited under conditions of marine inundation of tectonically neutral areas of the continental interior when adjacent positive areas are either peneplaned, submerged, or too far distant to supply significant quantities of clastics. Such shallow seas should be sufficiently warm to promote the growth of large numbers of carbonate-secreting organisms and the precipitation of inorganic carbonates from solution. The waters would be sufficiently clear to permit the penetration of sunlight to large areas of the sea floor and an accompanying maximum development of bottom dwelling faunal and floral elements. The resulting limestones, the "shelly facies" of Jones, are typically of three types: 1) normal marine, when precipitation by inorganic processes or algae exceeds contributions by macroscopic forms; example—Mission Canyon limestone (Mississippian) of Central Montana; 2) fragmental, when major contributions are made by benthonic animals (limestones of Osage age in the Mississippi Valley); 3) foraminiferal, an accumulation of tests of pelagic foraminifera plus inorganic precipitates (Cretaceous chalks) or an accumulation of tests of benthonic foraminifera (Pennsylvanian fusulinid limestones).

As a rule, platform limestones are thin, a few tens to a few hundreds of feet, and extend without marked change in character over very broad areas. They are generally light in color, reflecting thorough decay and removal of organic matter under shallow, circulating waters. Dolomitization is common, a feature which Twenhofel (p. 348) has interpreted as indicating stability of the site of deposition, permitting newly deposited sediments to remain for long periods near the base-level of deposition.

Dolomitization of normal marine limestones usually produces a rock characterized by saccharoidal textures and an abundance of dolomitized fossils or their casts (Racine dolomite of Northern Illinois) Dolomitization of fragmental limestones results in coarse crystalline textures in which traces of organic structures are distinguished with difficulty (numerous local examples).

Chert is common in platform limestones but much of it appears to be secondary in that bedding planes are commonly disturbed and enclosed fossils are silicified. Chert may occur as large isolated nodules or be confined to certain susceptible zones in a limestone sequence

Reef limestones, usually dolomitized, appear in the platform environment in isolated and discontinuous masses rather than in the linear trends typical of basin environments.

BASIN LIMESTONES

Basin limestones accumulate in intracratonic basins of the type termed "autogeosynclines" by Kay and of which the Michigan basin is an example. For long periods of time, such areas are tectonically negative, sinking as their load of sediments accumulates, and during these negative periods distinctive basin deposits are formed. At other times the basins are tectonically neutral and a such times the deposits are of the platform type, indistinguishable from those of the neighboring permanently neutral areas.

Basin environments can be divided into three types: 1) basins with open access to the sea, 2) barred or confined basins, and, 3) basin margins. In the first case, the chemistry and population of the sea occupying an open basin are unaffected by the negative tectonic potential of the underlying earth's crust, so long as deposition and subsidence are equal and coincident. Therefore, open basin limestones tend to be lithologically and biologically identical with platform types and distinctions must be drawn on the basis of relative thickness and lithologic associations. Isopach maps of limestone intervals indicate the location, ex-

tent, and shape of open basins in the absence of lithologic criteria, with thicknesses in the center of the basins being two to three times as great as those on the adjoining platform areas. Rarely, the negative potential of a basin may cause sinking in excess of filling by sediment. In these circumstances depth of water inhibits growth of benthonic forms and impeded circulation at depth promotes the gathering of undecayed organic matter. The result is a dense, black, largely unfossiliferous limestone, such as the Bone Spring limestone of West Texas, (King, p. 620).

Carbonate deposition in barred basins inevitably gives way to evaporite deposition if restricted waters prevail for a sufficiently long time. Under ideal conditions the following sequence of deposits leads from open basin deposits to evaporites: 1) normal marine or fragmental limestone, 2) dense limestone, sometimes associated with oolitic limestone, 3) dense and saccharoidal dolomite, 4) evaporties. The saccharoidal dolomites are unfossiliferous, often cross-bedded, and show evidence of accumulation as sand-sized rhombs formed as precipitates from abnormally concentrated solutions. The sequence described above sometimes is repeated in a series of rhythmic cycles, but omission of parts of cycles and repetition of incomplete cycles are common.

Margins of basins, the zones of demarcation between tectonically neutral platforms and tectonically negative areas, apparently meet the requirements for persistent biohermal growth more frequently than other areas of epicontinental sedimentation. Narrow but fairly continuous zones of reef limestones characteristically mark the margins of active basins, and, when mapped, serve as one of the readiest means of defining the limits of such basins. Recently Lowenstamm and Du Bois have discussed the methods of recognizing the subsurface occurrence of reef limestones and it is probable that further study will reveal many examples of reef systems as well developed as those of the Silurian and Devonian of the Michigan Basin and the Permian of the Delaware Basin of West Texas. Reef limestones are often associated with abrupt lateral facies changes, as, for instance, between platform limestones and basin evaporite cycles, and their accumulation is at least partially responsible for the isolation and restriction of some basin seas. Occasionally, the marginal lagoons peripheral to reef systems have been the sites of deposition of evaporites and evaporitic carbonates interbedded with red sands and shales. Such "back-reef" facies have been described by King (pp. 594–596) in the Chalk Bluff and Carlsbad formations (Permian) of West Texas.

GEOSYNCLINAL LIMESTONES

Geosynclinal limestones accumulate in extracratonic linear belts of marked negative tendency. Geosynclines are most often thought of as zones of extreme tectonic activity, both positive and negative, and as sites of predominantly clastic deposition; therefore, a geosynclinal limestone would seem to be a contradiction in terms. However, carbonates which can be identified as geosynclinal are not uncommon, particularly in the Paleozoic of the Cordilleran geosyncline. Such deposits must have formed when sinking of the trough took place independent of any rising and emergence of associated positive belts, or, less likely, when detritus from emergent positives was incapable of reaching the site of carbonate deposition. These conditions would be satisfied occasionally by Kay's "orthogeosynclines."

As in the case of inactive basins, limestones deposited in a geosynclinal belt during a period when no negative tendency is displayed are indistinguishable from platform limestones. When the normal negative tendency of a geosynclinc prevails carbonate deposition may occur under either of the following environments: 1) subsidence equal to, and coincident with deposition, or, 2) subsidence in excess of rate of deposition.

When subsidence and deposition are

equal the limestones do not markedly differ in character from platform limestones, as has been discussed for the equivalent situation in basins. Here, again, relative thicknesses and isopach mapping are the clues to the identification of the geosynclinal environment. Aside from information gained from associated clastic rocks and regional structures, isopach maps of limestone intervals make it possible to delineate geosynclinal borders and separate basinal from geosynclinal environments. Geosynclinal limestones are recognized by their considerable linear extent and by their great increase in thickness (five to ten times) over adjacent platform deposits. The Oquirrh limestone (Pennsylvanian and Permian) of Western Utah, for instance, is at least 26,000 feet thick; yet its equivalent on the platform areas of Central Utah is but a few hundred feet thick. Similar examples can be found in the Ordovician and Silurian of Idaho and Western Wyoming, and in the Mississippian of western Alberta. Unquestionably the abrupt changes in thickness have been magnified by eastward thrusting geosynclinal deposits, but even if palinspastic maps, as suggested by Kay, could be combined with isopachs they would still indicate enormous differentials in thickness over relatively short lateral distances.

Excess of subsidence over deposition, rare in the intracratonic basins, appears to be fairly common in geosynclines. At least, this is true if the dense, organic, cherty and sparsely fossiliferous limestones can be so interpreted. As in the case of the deep-water basin, dense texture is ascribed to depths inhospitable to bottom-dwelling organisms and resulting absence of coarse calcite fragments. The characteristic black color and rich organic content is explained in the manner offered by Twenhofel for certain black shales—impeded circulation at depth, with concomitant inhibition of bacterial decay. The abundance of chert is more difficult of explanation. It occurs in definite beds or intimately mixed with the limestone to produce a siliceous rock of almost equal and inseparable parts of silica and limestone. The chert contains few, if any, silicified fossils, although originally siliceous types such as radiolaria and sponge spicules are found. In all, the chert gives the impression of primary deposition, but the writer is at a loss for a reasonable explanation of the amount of silica represented in geosynclinal deposits (see Pettijohn, pp. 958–960). Dolomitization is uncommon in limestones of this type, and this, too, may be a function of depth. Kinderhook strata in the Rocky Mountains from Western Utah to Alberta and British Columbia are good examples of the rocks described above.

The two types of geosynclinal limestones often occur interbedded with one another, suggesting an alternation of deep and shallow conditions with some evidence of cyclical deposition.

SUMMARY

Characteristics of sediments typical of the three major environments of limestone deposition are summarized as follows:

Platform limestones: light colored normal marine and fragmental limestones, thin, but of wide areal extent, commonly altered to fossiliferous saccharoidal dolomite and crystalline dolomite.

Basin limestones: 1) open basins—limestones of platform type, but thickened as much as five to one over adjacent areas. Identified by isopach mapping and lithologic associations. 2) barred basins—sequential deposits from normal marine and fragmental limestone, through unfossiliferous dense and saccharoidal dolomites, to evaporites. 3) basin margins—reef limestones outlining the edges of subsiding areas.

Geosynclinal limestones: 1) shallow water deposition—limestones of platform type, but thickened from five times to more than ten times over adjacent areas. Identified by isopach mapping and lithologic associations. 2) deep water deposition—black, dense, cherty and siliceous limestones.

In considering these types it must be emphasized that when basins and geosynclines are tectonically inactive they exert no control over carbonate deposition and, hence, platform limestones may be interbedded with typical basin or geosynclinal types. Further, it should be clear that no single sample, or even a suite of samples, is sufficient to identify limestone environments. A three dimensional pattern plus detailed studies of lithologic associations must be obtained before rational interpretation can be made.

No mention is made in this paper of environmental data which may be gained from studies of insoluble residues, associated clastic lithologies, geochemical data, primary structures, or detailed paleontology. Each of these should be a fruitful source of valuable information.

ACKNOWLEDGMENTS

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FIG. 1, DECEMBER, 1947

COAL PARTINGS IN STYLOLITE SEAMS

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ABSTRACT

The occurrence of stylolitic coal seams in the Pottsville quartzitic sandstone of Lookout Mountain, Alabama, has been described by Stockdale as representing residual coal resulting from solution of quartz along fractures crossing the bedding at an angle of 25°. A photograph is submitted which shows four sections of two inch drill cores. These drill core sections, derived from the same source as the material used by Stockdale, show that the stylolitic coal seams are an integral part of an intricate cross-bedded structure.

The percentage composition of the rock consists essentially of 86.7 per cent of quartz, 13.3 per cent sericite and .009 per cent coal. Had solution occurred along a fracture as claimed, the residue would have been sericite instead of coal. That sericite would have become a residue is certain because most of the partings of the laminae of the crossbedded structure is sericite which has not been removed by solution. The facts therefore do not support the solution theory to account for the origin of the stylolitic coal seams.

It is the purpose of the writer to discuss the so-called stylolites of the Pottsville quartzitic sandstone from Lookout Mountain in Alabama. The material used in this research consisted of sections of two-inch diamond-drill cores which were supplied in 1944, while the writer was in the U. S. Army, by Richard W. Smith, District Engineer, Fifth District, Eastern Region, U. S. Bureau of Mines, and Don M. Couther, Project Engineer, Project 810, U. S. Bureau of Mines. Paris B. Stockdale, the ardent supporter of the solution theory for the origin of stylolites, apparently used similar material which he described and discussed (pp. 133–136) in 1945. As the writer cannot agree with the descriptions and deductions made by Stockdale, he wishes to present his views together with a photograph of four sections or short lengths of diamond-drill core which shows, without the use of line drawings, the general character and relationship of the stylolitic coal seams and the other cross-bedded structure of the rock. This type of illustration avoids the personal factors and presents the structural relationships without embellishments of any kind.

As Stockdale first described this material, it is best to examine some of his descriptions which are as follows:

"The laminae lie at an angle of 25° from the plane perpendicular to the axis of the drill core, suggesting a 25° angle of dip of the strata" (p. 133).

The stylolites were "developed along transverse fractures across the tilted bedding. The associated coal films, too, cut through and across the original sedimentary layers."

"Obviously, such a structural relationship has a significant bearing on the origin of the stylolites. Instead of being developed as primary structures along normal planes of sedimentation at or near the time of deposition of the original sediment (sand), the stylolite-seams came into being as secondary features subsequent to the original deposition and compaction of the sediments. They were developed along fracture-partings which originated at a time not only later than the original consolidation of the sediments into sandstone but even later than the metamorphism into the quartzite. Thus there is revealed another finding to be added to the already existing preponderance of evidence in support of the belief that stylolites are of secondary origin as held by the solution theory" (p. 135).

In contrast to Stockdale's interpretation that the stylolitic coal seams follow fractures across the tilted bedding, the writer believes that all of the seams and laminae present consist of elements of a normal cross-bedded structure of the Pottsville quartzitic sandstone. The evidence for this belief and interpretation lies in the relationships of the laminae in the structure of the rock which is clearly shown in the drill-core sections A, B, C and D, fig. 1. There is no evidence of fracturing or of a cross-cutting relationship of the thicker coal seams and the other seams or laminae.

Some of the thicker coal seams shown in section C, fig. 1 make an angle of approximately 25° to each other yet one would not be justified in assuming that any set of seams represent the true bedding and the rest represent fracturing at an angle of 25° to the bedding. As in all cross-bedded structures, there is a variation in the angular relationship of the seams or laminae. Those illustrated do not cross-cut and to project the lamination planes to lines of intersection beyond the specimens is indeed taking liberties with material of this kind. None of the planes were observed to merge into a common plane as in the topset and botttomset beds or laminae. The true bedding planes may not even be present in any of the sections illustrated.

It is difficult to understand how one could interpret the occurrence of the stylolitic coal seams in this instance as originating in fractures cutting across the tilted bedding. It appears therefore that the fracturing cited by Stockdale must be considered more hypothetical than factual and instead of having a "significant bearing" (p. 135) on the origin of the coal seams as residua of solution, his deductions appear to be quite unsupported.

The carbonaceous and muscovite-sericite seams and/or laminae appear to the writer to be unquestionably the result of normal sedimentary processes during the periods of least movement of the water when the lighter materials, were deposited as partings between the coarser and heavier particles of sand and the cross-bedded structure. The mica-sericite seams of the structure are the smaller and they are often exceedingly thin and inconspicuous. The coarser of these contain flakes of muscovite, which are often distorted by pressure, together with the fine grained variety sericite. In some of these seams there is often a sprinkling of coal in varying amounts. Most of the larger flakes of muscovite were probably deposited as such, although some recrystallization may have taken place during metamorphism. The sericite appears to be the product of the recrystallization of the clay and very fine-grained mica.

It is desirable to examine another statement made by Stockdale (p. 135) which needs further consideration and analysis:

> "The films of coal associated with the stylolites are a residual concentrate . . . . The insoluble constituents left from the dissolving of the stone. The originally disseminated bits of carbonaceous material became concentrated along the fracture where solution occurred."

A number of thin sections were made across several of the prominent stylolitic seams as well as from parts of the cores away from the coal. A micrometric study was made of the precentage composition of three slides covering an area along the seams to a distance of about 8 millimeters on each side. The percentage composition of the constituents in the seams as well as in the rock was determined. The micrometric work was done on a Leitz-Shand integrating stage.

The thin sections showed the rock to be a medium- to fine-grained quartzitic sandstone having grains of an average size of 0.2 mm. The largest grain seen in the sections was 0.5 mm. Considerably larger grains or granules were seen in the sawed sections of the cores.

The composition of the seams consists of 79.4 per cent of coal, 16.5 per cent of

muscovite-sericite and 4.1 per cent of pyrite.

The composition of the rock adjoining the seams consists of 86.7 per cent quartz and 13.3 per cent of muscovite-sericite. In addition the following minerals were seen in one or more of the sections but not on the lines of traverse: tourmaline, zircon, biotite and chlorite. In the 544.7 millimeters of traversing outside of the seams, 0.05 mm of coal was encountered on the lines of traverse. A few additional small fragments of coal were observed between the lines of traverse.

If one were to reduce the widths between the traverses to include all fragments of coal between the lines traversed, the ratio of coal traversed to the total distance traversed may still be smaller than 0.05 to 544.7, or 0.009 per cent of coal in the body of the rock. At a greater distance from the seams the percentage of coal is probably very much less than this amount for the slides which were cut at a distance of an inch or more from the coal seams do not show any coal.

When the percentage of coal is compared with that of sericite (0.009 to 13.3) in the rock one would expect to find a residue of sericite instead of coal. The majority of the seams are muscovite-sericite. The material of these seams was not removed by solution, hence, in the case of the stylolitic coal seams one could not say that the sericite in the rock was removed by solution along with the quartz and that only the coal remains as a residual product. This is an important and significant feature which the advocates of the solution theory for the origin of stylolites should explain.

The average width of the coal seams measured in determining the composition of the rock is 0.28 mm. in several of the drill-core sections the coal seams were thicker and exceeded a millimeter in thickness, section A, fig. 1, The combined thickness of the coal seams in section C, fig. 1 is considerably more than a millimeter.

The amount of quartzite that would have to be dissolved to produce a residual seam of coal a millimeter in thickness would exceed 10 meters (about 40 feet) if the rock contained as much as 0.009 per cent of coal. From the appearance of section C, fig. 1, one would expect that the full length of drill core may contain enough seams to amount to many millimeters of coal and an improbable amount of quartz would have to be removed to accumulate the coal as a residuum.

Owing to the insoluble nature of quartz in water it is indeed difficult to see how any large quantity of quartz could be removed in aqueous solution. In the event any appreciable quantity of quartz had been dissolved and removed, the cross-bedded structure would be severely truncated which does not appear to be the case.

The undulations, sinuosities and in some cases small stylolitic seams forming the cross-bedded structure in the Pottsville quartzitic sandstone of Lookout Mountain, illustrated in fig. 1, is believed to be entirely due to the usual processes of deposition of cross-bedded sands together with the adjustments occurring during compaction up to the time of the consolidation of the sandstone. The sand aggregate contained an appreciable quantity of colloidal material which is evident from the percentage of sericite now present. Under the conditions that must have existed at the time of deposition there must have been an appreciable quantity of colloidal and very fine-grained silica associated with the other materials. There was, therefore, no lack of plastic materials in the original sediments to permit the development of the diminutive stylolites and sinuosities along the coal and muscovite-sericite seams according to the contraction-pressure theory described by the wirter (pp. 53–54).

The occurrence of stylolitic seams of coal in quartzite fails to support the solution theory for the origin of stylolites as claimed by Stockdale for the following reasons:

1. The stylolitic coal seams in the specimens examined, and assumed to be

representative of the occurrence, do not cut across the bedding as claimed by Stockdale (p. 135).

2. The stylolitic coal seams represent an integral part of a cross-bedded structure, fig. 1, and therefore cannot represent a residual concentration of coal due to the solution of the quartz.
3. As the ratio of sericite to coal in the quartzitic sandstone is of the order of 1300 to 1 the solution of the quartz along a fracture should have resulted in a residual concentration of sericite instead of one of coal.
4. To assume the solution of the sericite as well as the quartz would fail to account for, or in reality overlook, the presence of the muscovite-sericite in the many seams of the cross-bedded structure.
5. To assume that the stylolitic coal seams may be residual concentrates along planes of the cross-bedded structure would meet the same objections given in three and four above.
6. The solution of such a great quantity of quartz, 10 meters to supply one millimeter of coal in the seams, is inconsistent with the insoluble nature of quartz.
7. The removal of even a few centimeters of quartz by solution would produce a marked truncation of the cross-bedded structure. None of the specimens examined show any evidence of truncation of the cross-bedding.

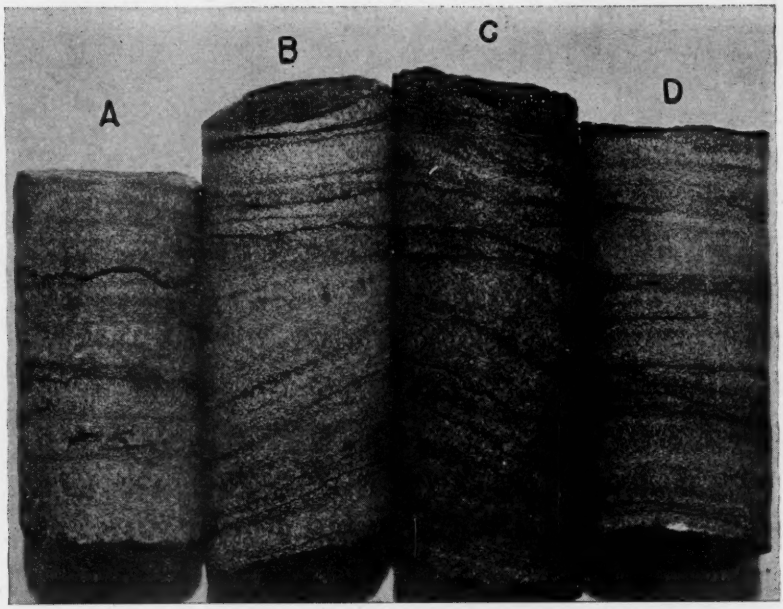

FIG. 1. Photograph showing four short sections of two-inch diamond drill cores of the Pottsville quartzitic sandstone from Lookout Mountain, Alabama. Sections B and C show strong crossbedded structure involving stylolitic coal seams. Section A contains a seam of coal about one and a half millimeters thick, while the sum of the widths of the coal seams in section C exceeds this amount. Sections B and D show mostly muscovite-sericite seams in the crossbedded structure. The angle between the bedding planes at the ends of section B is 22°. $X=0.67$.

8. The coal seams contain an appreciable quantity of pyrite (4.1 per cent) as well as muscovite, the latter being common in all of the seams or laminations. The occurrence of pyrite is consistent with a normal sedimentary origin rather than resulting as a residue from the solution of the quartzitic sandstone which does not appear to contain any pyrite.

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THE ENVIRONMENTAL SIGNIFICANCE OF CONGLOMERATES

W. H. TWENHOFEL

ABSTRACT

Gravels may be deposited under many conditions of environment and in themselves indicate only that some agent was competent to bring them to the places where they occur and that a source area was not too far distant whence they were derived. Certain features of gravel deposits, among which are imbrication and shapes of particles, cross-lamination, association with other sediments, and areal distribution, may indicate the environment in which deposition took place. Some features of gravels, among which is degree of rounding, may have been inherited from some earlier environment.

INTRODUCTION

Conglomerates and their composing gravels, like all other forms of sediments, are products of environmental conditions and inheritance, but they differ from most other kinds of sediments in that they are less narrowly limited by environmental conditions, may be deposited through a wide range of environments, and undergo essentially no diagenetic changes after deposition. Their composition has wide variation and they may be formed from essentially all kinds of rocks and even shale; mud and peat may produce gravels and boulders. Moreover, since the advent of artificial forms of rock, as glass, brick, pottery, and concrete, gravels have been formed from these. Beaches of some lakes in the Upper Mississippi Valley have pebbles and cobbles composed of wood and well rounded gravels of brick are common at some places on the east shore of Lake Winnebago.

It is possible for a sedimentary particle during its history to pass through many environments and receive an impress from each of them. As a rule, the impress of the environment immediately preceding deposition is the most obvious one and the work done on a particle in this last environment may obliterate all traces of effects produced in preceding environments. All features developed on particles in environments antedecent to the last are considered inherited. Thus, particles of a conglomerate of fluvial deposition may be released and enter a conglomerate of glacial deposition and this, in turn, may contribute to a conglomerate of marine deposition. If the last transportation was of brief duration and distance, inherited features might be the most obvious. This may be illustrated by the highly spherical and well frosted grains of some of the beds of the St. Peter formation of the Upper Mississippi Valley. These sands seem to have been deposited by water, but the sphericity and frosting are considered to have been produced by aeolian agencies and are thus inherited so far as occurrence in the St. Peter formation is concerned. The St. Peter formation, in turn, has contributed rounded and frosted particles to every formation deposited over the Mississippi Valley since the Ordovician and today it is making contributions of these sands to sediments deposited in every lake and stream valley which in any way has contact with the St. Peter formation.

As a consequence of the deposition of coarse clastics under many environmental conditions, a conglomerate in itself has no environmental significance beyond the fact that the competency of a transporting agent was adequate to place its constituents where they are found and that a source was not too far distant whence the particles were derived. Beyond these facts, a conglomerate probably has less meaning than any other

variety of sediment. However, the coarse particles deposited under each environmental condition may have acquired features for which the particular environment was responsible and these may indicate the environment of deposition. Such features consist of shapes and rounding of particles, sorting, orientation of particles in a deposit, presence of fossils, distribution and associations of deposits, and sedimentary structures in the conglomerates and interbedded sediments.

DEFINITION, PRODUCTION AND CHARACTERISTICS OF CONGLOMERATES

Conglomerates are composed of more or less rounded particles of pebble to boulder dimension as defined in the Wentworth scale. Most are composed of pebbles or (and) cobbles, but boulders are present in many. The particles may be rocks, minerals, or artificial materials which may or may not have been rounded during transportation. Transportation is generally done by water, ice, or mud flow, but strong winds may roll small pebbles, particularly if they have spheroidal or ellipsoidal shapes. Transportation in ice or in mud flow does not round particles and these remain unmodified except as they are held against the base over which movement takes place or against an adjacent rock. Any agent of transportation may acquire particles which had previously been rounded by some other agent. The rounding of particles may or may not be a measure of the extent of the latest transportation.

Shape of particles of conglomerates vary greatly, but most particles of long transportation have shapes in the range from disk-shaped to ellipsoidal or spheroidal. Less traveled particles are in some intermediate stage from angular to well rounded. Rocks generally break into particles of two long and one short dimension, or two short and one long dimension, the former far more common than the latter and particularly characteristic of rocks which have an easy direction of cleavage as is the case for most sedimentary and metamorphic rocks. The former produces disk-shaped particles, the latter ellipsoidal. As few particles on detachment from parent rocks have cubical shape, it results that spheroidal particles are not generally common, but they are abundant on some beaches. This is thought to be a consequence of selective transportation. Landon suggested that spheroidal shapes were the first stage in the rounding of beach gravels and that they became flattened later. Cailleux's observations support the view of Landon. The writer's observations and those of Grogan are not in line with this suggestion. Long traveled gravels are usually well rounded and composed of hard and tough rocks or minerals. Excellent rounding, however, is not a measure of long travel as soft rocks, like limestone and marble, become well rounded after relatively short travel. Wentworth (1919) rolled cubes of white marble in a wood-lined metal drum and all evidence of original cubical shape had disappeared after 94 miles of travel and the particles fitted description of well rounded. Extent of rounding in stream gravels may be commensurate to distances from sources, but the gravels of beaches and the adjacent bordering waters may travel for hundreds of miles and never be more than a few miles from sources. Most gravels have frosted or mat surfaces. Rounding of gravels has been studied by many students, among whom are Barrell, Cailleux, Gregory. Krumbein, Landon, Mansfield, Trowbridge, Wadell, and Wentworth.

Gravels are rarely well sorted. This arises from the fact that transportation is mainly by traction and large and small particles travel together. The large particles after deposition imprison the smaller ones within their interstices and protect them from removal. Moreover, when decrease of competency compels deposition of a tractional load, the coarsest part of any suspended load is also dropped on any gravels already deposited where the small particles settle into unfilled interstices.

Aqueous currents tend to place the

particles of gravels in certain characteristic positions. Particles with two long and one short dimension tend to be inclined in up-current direction; particles of two short and one long dimension tend to come to rest with the long dimension normal to directions of currents. Particles in mud flows or deposited directly by ice are unsystematic in arrangement.

Conglomerates do not commonly contain fossils and those present are generally much broken and abraded. Associated sandstones may contain excellent fossils which usually are excellent criteria for determination of environment or deposition.

The areal distribution of conglomerates varies to a considerable degree with the environment of deposition. The plan of a stream deposit tends to be linear, but such is also the plan of a deposit made on a beach, over some parts of the neritic zone of the sea, in an esker, and over a piedmont area. Most fluvioglacial gravels have fan-like deposition, eskers excepted. Some neritic gravels are in the form of extensive sheets.

Sedimentary structures of conglomerates and associated sediments consist of cross-lamination, ripple marks, mud cracks, and kindred features. Certain forms of these features are characteristic of particular environments of deposition.

The associations of conglomerates with other forms of sediment are perhaps the most reliable criteria for determination of environments of deposition. It is usually not difficult to prove that a conglomerate was deposited in the same environment as the associated sediments.

VARIETIES OF ENVIRONMENT

Environments are infinite in their variations and each passes laterally in space and vertical in time into others. A relative movement of sea level may change a place from a continental to a marine environment, or a marine to a continental one. For purposes of convenience three classes may be made which are continental, mixed continental and marine, and marine.

The continental environment may be divided into the terrestrial with the two divisions of glacial (including fluvioglacial) and desert; and aqueous with paludal, fluvial, lacustrine and cave divisions. The fluvial has the two phases of piedmont and valley flat. Gravels are deposited in every continental environment; they are uncommon in swamps and have little significance in caves.

The marine environment has three divisions which are generally known as neritic, bathyal, and abyssal, divided in the basis of depths of 600 and 6,000 feet. Gravels are readily deposited over neritic bottoms where they form interformational conglomerates; they may be present over some parts of bathyal bottoms which they generally reach either by sliding or rolling from neritic bottoms, and it is possible that sliding may bring gravels to abyssal bottoms, but such is not considered a common occurrence. Rise of sea level or sinking of a part of the crust may bring neritic bottoms to bathyal and possibly to abyssal depths so that gravels of the neritic environment may become succeeded by deposits of the bathyal or abyssal environment.

The mixed continental and marine environment contains the littoral, delta, marginal lagoon and estuary. The delta environment is considered in connection with streams, the others with beaches and the sea. Deposits of gravel may be made in any of these environments which frequently can not be differentiated from the gravels of other environments.

CONGLOMERATES OF THE MARINE ENVIRONMENT

Conglomerates are deposited in the marine environment by strong currents moving outward from a coast, crossing its indentations, or on the bottoms of funnel-shaped bays into which shore currents move from both sides so that strong currents move seaward along the axes of the bays. The particles of these conglomerates tend to be well rounded as they were derived from a beach where this characteristic of gravels seems to be best accomplished. Some gravels on neritic bottoms may be little rounded.

This is the case where a beach is not present because of deep water at the shores so that rock fragments drop from cliffs directly into water, or where a coast is being so rapidly eroded that rock fragments are swept away almost immediately following detachment.

As Barrell has noted (p. 292), coastal charts indicate that gravel is essentially a beach formation and thickness in shallow water can not be great except under conditions of rising sea level. The writer agrees with this statement, but qualifies it by excepting those sea bottoms over which deep water extends to the shores. There are bottoms on parts of the present coast of Newfoundland which permit the accumulation of a great thickness of coarse materials. There are places on the south coast of that island where it is now possible for coarse clastics to accumulate with stillstand position of sea level to a thickness of nearly 2,000 feet and to a thickness of 1,000 feet in more places. The waters are that deep within a mile or two of the shore. Barrell (205) states that "on open coasts with fixed shore line marine gravels commonly range from about 1 fathom above high tide level to 4 to 5 fathoms below. They are kept against the coast and seldom extend more than 3 miles from shore." "The thicker deposits arise in connection with curving shores, especially on young ones, where the deposits of gravel may either fill bays or build out as spits and promontories. Exceptionally concentrated undertow from shore reentrants may sweep out gravel to depths of 20 or 30 fathoms, and storms cooperating with tides may sweep across bottoms to depths of 20 to 30 fathoms and up to 10 miles from land. Marine gravels of fixed shore lines, therefore, though ordinarily deposited within 3 fathoms of water and within a mile of land, may under exceptional circumstances extend to ten times these limits" and "the most favorable conditions for the accumulation of thick marine conglomerates are those where the sea is transgressing (rising) against a land of some relief." Nevertheless, on parts of the south coast of Newfoundland where deep water exists at the coasts and angular fragments drop directly into deep water, gravels are thought to be in process of deposition to depths of 300 or more fathoms. With rising sea level on a coast like that of southern Newfoundland it would be possible for gravels to accumulate to a thickness of several thousand feet. Even shallow water might have repeated occurrences of conglomerate through great thickness should there be subsidence of the sites of deposition as then marine currents could deposit gravel over the shallow bottoms through a thickness equal to the extent of subsidence. As most great sections of the geologic column denote subsidence, it is possible that gravel deposits over neritic bottoms may have accumulated to great thicknesses. It is believed that this was the case in the Ordovician and Silurian of northern Newfoundland where there are thousands of feet of sections in which gravels are present on many levels, in the Ordovician and Silurian section of Anticosti Island where gravel bands are scattered through around 2,000 feet of section, in the Cambrian of the Upper Mississippi Valley in some formations of which gravels derived from Cambrian strata are not uncommon, and in the Paleozoic of the Baraboo Range where gravel beds of marine origin interstratified with sandstones and shales were spread outward from the Huronian quartzites.

Neritic bottoms, and such may also be present in lakes and streams, not uncommonly have deposits which resemble gravels and have been mistaken for them. These differ from true gravels in that the particles are of accretionary origin. They are pseudogravels and form pseudoconglomerates of which most are due to certain algae which build ellipsoidal or spheroidal bodies of concentric internal structure. These may undergo some transportation and some smoothing of surfaces before burial and may form a clean, well sorted deposit. They have been mistaken for true conglomerates in

the Silurian limestones of Gotland where they occur in association with coralline limestones and in a formation of the Permian in the Arbuckle Mountains of Oklahoma. These do not have the significance of true conglomerates unless they have been transported, but they do indicate water of depths within the zone of light. Spheroidal, ellipsoidal and disk-shaped coral heads and concretions may make similar deposits. Only if the coral heads are of primary deposition is a marine environment indicated.

Distribution of units of neritic gravels should be patchy and the plan of each unit should be rudely circular or elliptical except for units made along axes and across entrances of bays where distribution would tend to be linear. Units of gravels would be interbedded with other forms of marine sediments, and in the case of large lakes, with lacustrine sediments. Distribution of neritic gravel might be in the nature of a sheet with considerable length parallel to a shore line as compared to width normal thereto. If marine gravels are deposited under conditions of a rising sea level, patches would ascend in the section with most moving landward as sea level rose. If a deposit was in the form of a sheet, it would ascend landward with rise of sea level, incline seaward, and transect time diagonally.

In general, an occurrence of well-rounded gravel of considerable distribution suggests, but does not prove, that deposition was over neritic bottoms. On the other hand, occurrence of an extensive deposit of angular gravels does not prove that the environment was not marine as the water may have been quite deep at the shore and particles dropped directly from cliffs into water, or shores were being so rapidly eroded that beaches could not form. In both cases particles were spread without much abrasion.

Most marine deposits of gravel were made by currents which did not always move in the same direction and particles, as a consequence, imbricate in different directions in different beds. According to Cailleux (1945), inclination of particles in marine gravels ranges from 2 to 12 degrees. Cross-lamination is not a common feature of gravels, but marine gravels are commonly interbedded with sands which may have this feature with different directions of inclination in different beds. Both wave and current ripple mark may be present in the sands and the latter would be likely to show movement of currents in different directions. Mud cracks would not be present in any associated mudstones.

Well rounded gravels on neritic bottoms are likely to be fairly well sorted. Angular gravels may not be. Sands which fill interstices may or may not have good sorting. The sands, however, are usually clean.

Coarse sediments are not common over bathyal bottoms. It is possible for such materials to be deposited directly if descent to bathyal depths is steep, but it seems likely that most reach bathyal depths by sliding from shallower bottoms as now could readily be done on parts of the south coast of Newfoundland and in such regions as the East and West Indies where steep slopes to great depth are present in some places and the frequent earthquakes which occur in the Indies would tend to jar deposits of shallow depths and start the sliding. Gravels of this deposition would show their origin by the diverse positions of the particles, the disturbance of stratification, and in the muddy character of the associated deposits and the materials forming the matrix. These features, however, would not indicate depths of deposition before sliding started or the depths where sliding stopped. The places of deposition before sliding might have been over neritic bottoms or some other environment of higher position and the sliding might have been brought to an end on a low part of neritic bottom.

GRAVELS OF BEACHES

Beaches are not present on sea and lake shores if deep water margins the land as then particles drop into water and at once become parts of neritic or bathyal

deposits. Beaches also may not be present if wave and current transportation are competent to remove fragments as rapidly as detached from shores. These are moved along shore to inlets or swept out to sea. Such is the case on many parts of the north coast of Anticosti Island, on the Oregon coast and other coasts known to the writer. Many miles of the coast of Oregon, Washington, and the Atlantic Coast from New York to Florida have no gravels on the beaches either because the shallow waters bordering the coast limit the erosive power of the waves or because the coastal materials can not furnish gravels. Where coastal rocks are hard and tough, water is not too deep at the shores, and wave action can reach coasts with not too much competency, beaches with gravels may be present.

Coasts that are being eroded leave behind a wave-cut terrace at the level of downward erosion at each place. This terrace remains free of deposits until a rise of sea level places the seaward part below the limit of active erosion after which this part may receive deposits of gravels, sands, muds, or calcareous materials. Wave action on shores with beaches generally keeps gravels with the beaches as the competency of the incoming waters is commonly stronger than the outgoing. Times of strong waves and currents may strip beaches bare of gravels and sands which either are taken seaward or moved into bays.

Beach gravels range from poorly to excellently sorted and rounded. In general, large particles are mingled with smaller ones and matrix materials consist of sands, pebbles and rarely of mud. In places, the character of beach materials changes rapidly and frequently. Shapes range from very angular to highly spheroidal (rare), ellipsoidal and disk-shaped. The oft-quoted statement that beach gravels are characteristically disk-shaped because of method of wear on beaches and that beaches are the only places where such shapes develop seems to have little basis in fact. Although this shape is common among beach gravels, other shapes are equally common and disk-shaped particles are also found in stream deposits.

Gravels of beaches tend to be well washed, but they are not always so. Particles commonly imbricate away from the land and toward the water, particularly on the lower parts of beaches. There are reversals of this inclination. Cross-lamination is generally not conspicuous in beach gravels, but it may be present in interbedded sands. Forests are generally short and inclination most commonly is toward the water if the cross-lamination is due to water, but there is much wind drifting of sands on beaches and this may produce cross-lamination with inclination in any direction.

Gravels of beaches tend to be ephemeral deposits and they are buried beneath other deposits with great difficulty. They move inland with the beaches as the shores are eroded and ultimately the particles are worn to sand and silt and move out to sea to attain deposition on neritic bottoms. The thickness of beach gravels at any one time at a place can only be from a little below low tide to the heights reached by the highest waves. This in extreme cases may be as great as 50 feet and is less than 15 feet in most places. Only a very rapid rise of sea level could bring beach gravels below the level where they could not be eroded or moved shoreward. It is thought that this does not often take place and that there are few deposits of marine beach gravels in the geologic column.

Beach gravels are not common on the shores of small lakes as there is not sufficient wave erosion to produce them. They may be present as inherited features. They are common on the beaches of large lakes where they have the same characteristics as those of marine beaches except that they are not likely to be so thick. These gravels have possibility of preservation in the geologic column as a lake may be brought to extinction by filling and the beach gravels could then be buried.

Beach gravels, if preserved, should

have linear distribution, should be poorly to excellently sorted, matrix material should be poorly sorted, particles should commonly imbricate seaward or lakeward, and cross-lamination of aqueous origin should have short foresets inclined for the most part toward the water. Distribution should be patchy, lie over a wave eroded surface, and the gravels should be the basal conglomerate of marine or lacustrine deposit. Distribution would tend to be parallel to the average strike of the cross-lamination.

CONGLOMERATES OF CONTINENTAL ORIGIN

Conglomerates of stream deposition have imbrication of the composing gravels commonly inclined upstream and the long axes of the particles of ellipsoidal shapes are dominantly perpendicular to current direction, cross-lamination is not obvious, but as stream gravels are generally interbedded with sands these may be cross-laminated with inclination almost always downstream. Calleux (1945) states that inclinations of particles are in the range from 5 to 30 degrees. Sorting is generally poor, deposits are usually not clean, and muds and sands fill interstices in the gravels. The units (not the particles) of conglomerate have linear distribution parallel to the inclination of the cross-lamination. This is very different from what obtains in beach gravels. Each unit is commonly of the nature of an elongate lens in sands. As channels of aggrading streams shift, so do the deposits, hence linear deposits of much irregularity and serpentine plan develop. The gravels tend to have erratic distribution in the associated sands, or rarely, they may form a sheet which has a different stratigraphic level at different places. The combined thickness of associated stream-deposited gravels and sands may be very great and in a subsiding valley it would be possible for gravels and sands to accumulate to a thickness equal to the extent of subsidence.

Gravels are rarely deposited in large deltas. They are rare in the delta of the Fraser River of British Columbia despite the fact that the front of the delta is only about 50 miles from high mountains. Gravels are very rare in the delta deposits of the Mississippi River and they do not seem to have been reported from the deltas of the Nile and the Amazon. Gravels in the deltas of large rivers should be long traveled and particles should be small, well rounded and composed of resistant rocks or minerals. They should constitute only a small part of the deposits.

There are some conditions under which a delta deposit may contain abundant gravels. A river flowing directly from high land into the sea or a lake would retain its competency to transport large particles to its entrance into the body of water into which it flows. Under these conditions it could transport and deposit gravels with some of the characteristics of those deposited over valley bottoms. Gravels would be likely to be abundant in the earliest deposits of such a delta and would decrease in quantity and increase in roundness with delta building and reduction of source areas, and after source areas had become lowered and a delta had become extensive there might no longer be competency to carry coarse materials to or across it. Some of the poorly sorted gravels in the Ordovician and Silurian of northern Newfoundland may have been deposited under these conditions. Deposits might be of great thickness if a delta lay over a subsiding area, would be poorly sorted, angular particles would be common and the deposits would not be clean.

Deposits over piedmont areas are made by rapidly flowing and turbulent waters which are not permanently confined by channel walls. Deposits from time to time choke channels and force the waters to change position. Initial dips are down current and may be as great as 15 degrees, and cross-lamination is inclined in the same direction. Stratification is very irregular. Gravel distribution tends to be linear for each unit, but there

is great irregularity and near the head of a piedmont area the deposits may consist almost entirely of unorganized masses of gravels and boulders. Deposits are poorly sorted and this applies not only to the gravels and boulders but also to all associated materials. Particles may or may not be well rounded if in the first cycle of deposition. Gravels generally dominate in the upper part of a piedmont deposit, sands in the middle part, and silts and clays in the lower part. Large angular boulders may be present in large numbers at any place and most of these were probably brought in mud flows. The plan of a piedmont deposit is rudely fan-shaped.

Glacial and fluvio-glacial gravels are deposited in moraines, kames, delta kames, eskers, and outwash fans. Gravel and boulders are mingled with sand, silt and clay in moraines, there is no sorting, and rounded particles are generally not present unless the rounding was inherited from an earlier deposit. The large particles are irregularly distributed in the sand, silt and clay and they may constitute a small to large part of a deposit. There is no stratification of the ice-deposited materials of moraines.

The gravels of kames, delta kames, eskers and outwash fans are deposited by water currents under particular conditions. Sands are interstratified to a greater or less extent and in some cases they compose most of a deposit. Gravels tend to be clean, washed, are poorly to well rounded, and the matrix is generally composed of clean but not well sorted sands. Sorting is fair in out-wash fans. Considerable slumping seems inevitable in deposits of kames, delta kames, and eskers with disturbance of stratification and sorting, this being particularly true for gravels of eskers. Inclinations of stratification in kames and delta kames may be steep and in extreme cases may be as great as 30 degrees. Thickness may exceed 100 feet, but is generally considerably less.

Von Engeln stated that glacial cobbles have a roughly triangular or flat iron shape and that they moved with the pointed part of the "iron" ahead and the flat side down. The writer can not agree with this generalization. Most particles are without striations.

Deposits of kames have fan-like plan of limited dimension; those of delta kames have the same shape but are of larger dimension. The plan of outwash fans is also fan-like but dimensions are larger than those of delta kames. Gravels and associated deposits of eskers have linear distribution. Gravels of outwash fans and delta kames grade into finer deposits with distance from the glaciers which produced the waters of deposition.

Desert gravels were formerly associated with finer materials that have since blown away and, generally, they constitute a thin protective veneer over finer materials. Deposits rarely become thick, but as some deserts lie upon piedmont surfaces with streams losing themselves on lower levels by evaporation and sinking into the deposits, it results that ventifacts and particles with desert varnish may be distributed through considerable thicknesses of deposits.

Desert gravels tend to have polished or etched surfaces and desert varnish, which may have an almost mirror finish. Wind-cut facets may develop to form ventifacts, and interbedded sands may be of beach, valley flat, or piedmont origin. These sands may have current ripple marks and have both aeolian and aqueous cross-lamination.

Mud flow and landslide gravels are without sorting and stratification, are not washed, particles are commonly angular, and usually gravels of these origins are parts of other deposits. They resemble gravels of moraines but have less extensive distribution.

GRAVELS AND UNCONFORMITIES

Most elementary textbooks of geology emphasize the presence of a conglomerate above an unconformity and tend to leave the impression that such is an invariable accompaniment of this sedimentary structural feature. It is certainly true

that this is not always the case in marine sediments. Erosion of a shore with still-stand position of sea level produces a wave-cut terrace on which no permanent deposits are made. Any rise of sea level might permit deposition of sediments over its seaward borders and these would be more likely to be calcareous sediments, muds, or sands than gravels so that in most places a basal conglomerate would not be present. Illustrations of this condition may be seen on the brink of Montmorency Falls near the city of Quebec, Canada, where the Trenton limestones lie directly on Pre-Cambrian gneiss without a sign of clastics; in the Beargrass Creek quarries near Louisville, Kentucky where Middle Devonian limestone lies directly on Middle Silurian limestone without a basal conglomerate, and in the Upper Mississippi Valley where the Oneota dolomitic limestone (Lower Ordovician) lies on Upper Cambrian sandstone with only an occasional rare pebble or cobble. However, in the Baraboo Range of southern Wisconsin, wherever the Cambrian or Ordovician formations have contact with the Huronian Baraboo quartzite, there is present a marginal conglomerate which in most places seems to be a shore deposit where there was no beach. In some places in that region there was a beach and shore gravels were spread over shallow neritic bottoms. Most conglomerates seem to be interformational in that they lie within and not at the bases of formations. Gravels of continental origin seem to be those most abundant.

SUMMARY

1. Conglomerates in themselves are not indicative of any environment and merely show that some transporting agent had sufficient competency to bring particles from a not too distant source to the places where they occur. An agent of less competency may have removed associated smaller particles and left the larger ones.

2. Areal distribution, sedimentational structures, associations with other deposits, shapes, and roundness of particles, and associated organic remains are possible means to determination of environments of deposition. In general, no single characteristic is adequate for this determination.

3. Rounding of gravels may have been produced during the last transportation, or this feature may have been inherited from some earlier deposit of gravels. Degree of rounding is a rough measure of distances of transportation, but may have little relation to distances from sources.

4. Shapes and roundness of particles are considered to have little significance so far as aqueous environments are concerned.

5. Beach gravels, valley flat gravels of streams, some marine gravels and gravels of eskers have somewhat linear distribution which may be very patchy for those of streams and beaches. Beach gravels are thought to be rare in the geologic column. Some gravels deposited in the neritic environment cover somewhat equidimensional areas. Piedmont and valley flat gravels and associated deposits are rudely fan-shaped and the gravels are lenses distributed irregularly in finer materials which they may or may not exceed in quantity.

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FIGS. 1–7, MICROPHOTOS 1–12, DECEMBER, 1947

DIATOMACEOUS DEPOSITS AT LAKE TOBA

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ABSTRACT

Various diatom species lived in the beginning of the Quaternary period in Lake Toba (±2500 km²), situated in Northern Sumatra.

In consequence of the very favorable circumstances that prevailed in this caldera after eruptions of acid rhyolitic tuffs, enormous deposits of freshwater diatoms were formed.

At present the deposits lie bare and reach to about 150 meters above the level of the lake which fell about 250 meters because of a breaking through at the Asahan gap. Transportation to the coast is at present still too expensive to allow a profitable exploitation of the diatomite of the Toba district, though it is of good quality.

INTRODUCTION

The Toba caldera, situated in the North of Sumatra (fig. 1), has a surface of about 2500 km² (Lake of Geneva, 582 km²; Dead Sea, 915 km²) and was formed in the Quaternary period by the first eruption of the Toba volcano. This eruption covered an area of about 2000 km² (v. Bemmelen) with ejected rhyolitic material, mainly loose tuff.

Shortly afterwards the second Toba eruption occurred which, however, was of less importance. During this eruption the bottom of the caldera, which meanwhile had been filled with rainwater, was uplifted at both sides of the eruption point, thus the isle of Samosir and the peninsula of Sibolangit were formed. The first was raised a few hundred meters higher than the second (v. Bemmelen) and shelves away on its west side. The peninsula of Sibolangit slopes gently at the east towards the foot of the Si-Manoek-Manoek mountains (highest point 1216 meters).

After the second eruption, whose centre was situated between Samosir and Sibolangit, the caldera filled with water to the highest point of the Asahan gap, ±1150 meters, i.e. the lowest point of the surrounding mountains. Ancient shore terraces are still visible on the mountain sides at a height of 1050 to 1150 meters (Klein).

Enormous numbers of diatoms lived in this caldera lake under very favorable circumstances and produced huge deposits of diatomaceous earth. Afterwards, a rapid lowering of the level of the lake took place to the present mark of about 906 meters (probably in the rain stage of glacial period) in consequence of forced erosion (breaking through) at the Asahan gap. This resulted in the exposure of the diatomaceous deposits which, owing to their consistency, shifted slightly towards the lake (angle of inclination: 5 to 8°).

Diatomaceous deposits

A. *Appearance*

a) Samosir

The most characteristic diatomaceous deposits are found on Samosir mainly on the west side and there especially north of Pangoeroeran, i.e. in the feebly inclined parts of the island. These deposits (fig. 2) reach a height of ±150 meters above the level of the lake. The layers become thinner and the diatomite purer with distance above lake level. The thick layers, the most soiled with tuff and organic material, are found in the lower reaches of the diatomite formations (fig. 3).

Higher up only a little pure white siliceous earth covers the surface (fig. 4).

Figures 2 and 5 depict very pure,

figures 3 and 6 impure diatomite. There are fewer sand and clay layers in the pure deposits and these interjacent layers are thinner than in the impure deposits.

b) Balige and Porsea

At the shore of Lake Toba near Balige and Porsea stretches an extensive, flat area, that is the bottom of the old, vast lake. Drillings prove that in the plain between Balige and Porsea there is diatomite to a depth of 9 or more meters, interrupted only by a few thin layers of rhyolitic sand. On fig. 7, taken in this plain, one clearly sees that the diatomite is a little below the surface. It is only pure at the upper part (notice the white layer). Below comes impure diatomaceous earth of a grayish-green color to a depth of 9 or more meters, which, because of its originating on the flat bottom of a lake, contains organic matter (see Table I).

c) Other places

Deposits of diatomite are found at a considerable height on Samosir (1360 meters) along the highway from Balige to Si Borong Borong at the kilometerstones 105 and 106 (±1150 meters) and at the kilometerstone 89 (±1270 meters) (Ruttner). These are, however, only small, local deposits originating in small lakes; consequently independent of the huge deposits mentioned here before. Still today one finds these small lakes not only on Samosir, but also scattered all along the highlands around Lake Toba (plateau of Pak Pak, ±1650 meters; Toba upland plain, ±1250 meters). They are inhabited by the same diatom species (microphoto 1) that we know from the fossil deposits of the ancient Lake Toba (microphotos 2–12).

That important diatomaceous sediments are no longer formed in the present-day lakes is due to the unfavorable circumstances under which the diatoms now live (water polluted by organic substances etc.—see below).

B. Species

As is shown by figures 2 to 12, different diatom species prevail. It is very remarkable to notice that this may even happen when the places where the samples are taken are only short distances from each other. Brockmann, who examined the mud of the Elbe Bight near Wilhelmshaven (Germany), also mentioned this.

The various species in the diatomite deposits of Samosir and Balige-Porsea may even stand out separately to such an extent that one can speak of a "pure culture" (figs. 3 and 5).

The fibrous kind of diatomite that shows a honeycomb structure (fig. 5) when broken always consists mainly of the species with long needles—*Synedra rumpens* (fig. 3).

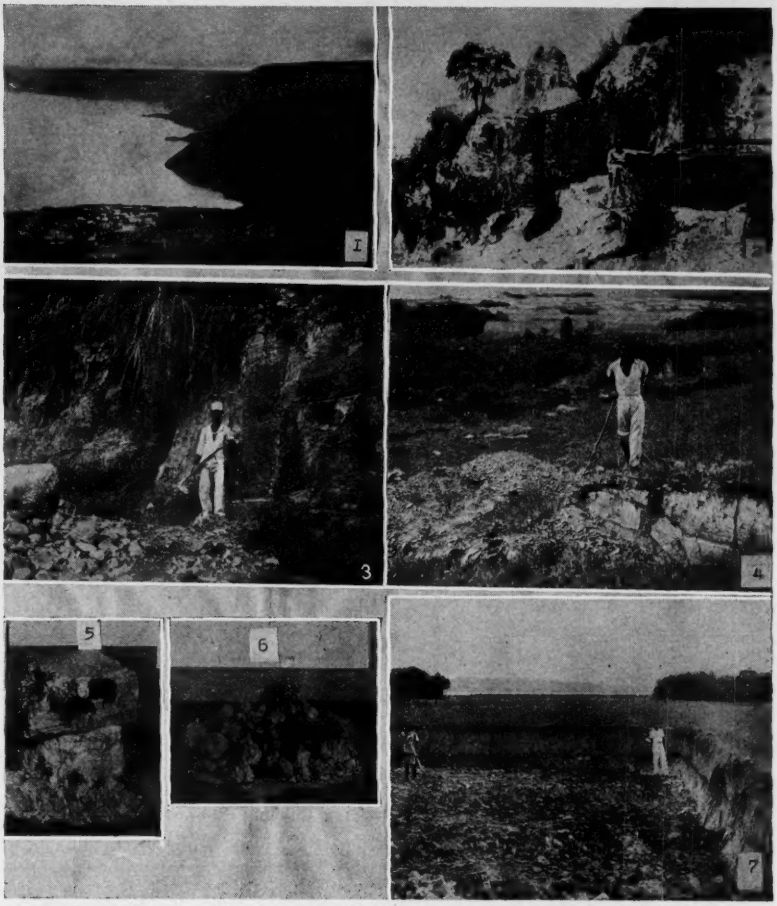
In the plain between Balige and Porsea the friable, white pure kind is composed mainly of the species *Denticula* and such is also the case in the grayish-green impure kind which lies underneath. Drilling in this wet subjacent layer, which has a depth of several meters, gives the impression of a jelly.

C. Analyses

The figures of Table I show that the pure, white Toba diatomite is of a very good quality in comparison with that which is explored everywhere else (Calvert-Kenny). Even the grayish white, fairly pure Toba diatomites are good. The grayish-green, impure varieties contain much organic matter (notice high loss on ignition).

D. Extent of the deposits

The surface of the pure diatomite deposits to the north of Pangoeroeran embraces more than 125 hectars. This gives, with an average thickness of 80 centimeters, 1,000,000 cubic meters. To this must be added the impure diatomaceous earth with an average thickness of about 2 meters and spreading over a surface of ±500 hectars, amounting to ten million cubic meters. Between Balige and Porsea diatomaceous earth certainly extends over more than 1250 hectars. With the thickness of 9 meters for these deposits,



Ordinary photos

No. 1. View of Lake Toba from the Karo plateau (±1250 meters).

No. 2. Deposit of diatomaceous earth, grayish weathered on the outside. The upper part consisting of pure fibrous diatomite (*Synedra rumpens*)—Samosir.

No. 3. Impure diatomaceous earth mixed with organic material and clay, gray-green color, interspersed with a few pure white diatomite layers—Samosir.

No. 4. Diatomite on the surface at ±150 meters above the level of the present lake—Samosir.

No. 5. Pure white diatomite with clearly visible honeycomb structure and consisting mainly of *Synedra rumpens*—Samosir.

No. 6. Impure diatomaceous earth, gray-green color from the subsoil of the Balige-Porsea plain.

No. 7. Diatomaceous earth in the Balige-Porsea plain. Above about half a meter of cultivated soil. Then to a depth of about one meter white, pure diatomite; underneath gray-green impure diatomaceous earth to a depth of at least 9 meters.

TABLE I

Description	Pure diatomite white		Fairly pure diatomite grayish white		Impure diatomite grayish green	
	No. 8	No. 12	No. 6	No. 15	No. 2	No. 5
A. *Material dried in the air*						
a) volume weight	0.08	0.07	0.19	0.23	0.30	0.29
b) moisture (%)	6.2	7.2	7.–	8.1	6.2	5.7
B. *Absolutely dry material*						
a) loss on ignition (%)	1.8	1.9	5.7	6.5	11.6	10.7
b) nitrogen (%)	0.04	0.04	0.06	0.07	0.20	0.14
c) insoluble in HCl-HNO_3 (%)	94.5	95.5	88.5	89.5	81.8	85.–
d) soluble in HCl-HNO_3						
$Fe_2O_3+Al_2O_3$ (%)	1.32	1.32	3.23	1.90	3.40	2.98
CaO (%)	0.07	0.09	0.18	0.18	0.15	0.14
MgO (%)	0.07	0.04	0.37	0.26	0.35	0.29
K_2O (%)	0.06	0.05	0.15	0.11	0.14	0.13
P_2O_5 (%)	tr.	tr.	0.04	0.02	0.03	0.02
			Mn_3O_4 = *traces*			
C. *Absolutely dry material insoluble in HCl-HNO_3*						
SiO_2 (%)	92.5	93.–	90.–	89.–	84.–	90.5
$Fe_2O_3+Al_2O_3$ (%)	5.7	6.–	8.3	9.4	13.8	8.6
CaO (%)	0.4	0.6	0.3	0.2	0.2	0.2
K_2O (%)	0.7	0.7	1.2	0.8	1.2	0.7
Na_2O (%)	0.5	0.4	0.8	0.8	0.6	0.5
			MgO-Mn_3O_4-P_2O_5 = *traces*			

EXPLANATION OF FIGURES

Microphotos (dimension diatoms $\pm 5 \times 100\ \mu$).

No. 1. Mud of algae from Lake Toba consisting among other species of *Denticula granulata* var. *curvata*.

No. 2. Gray-white, fine rhyolitic tuff mixed with diatomite. Mainly *Cyclotella meneghiniana*, Samosir.

No. 3. White diatomite of fibrous structure, very pure. Mainly *Synedra rumpens*. Also a few *Cyclotella meneghiniana*, Samosir.

No. 4. White diatomite of loose structure; very pure and consisting of *Melosira granulata* var. *valida*, *Denticula pelagica*, *Cyclotella meneghiniana*, *Pinnularia viridis* and other species. Samosir.

No. 5. Diatomite consisting mainly of *Melosira granulata* var. *valida*. Besides also some Cyclotella meneghiniana, Samosir.

No. 6. As 5, but consisting of *Denticula pelagica*, *Denticula lancelota* and *Melosira granulata* var. *Jonensis*, Samosir.

No. 7. As 5, but consisting of *Denticula pelagica*, *Denticula amphicephala* and *Melosira granulata* var. *curvata*. Moreover a few sponge spicules, Samosir.

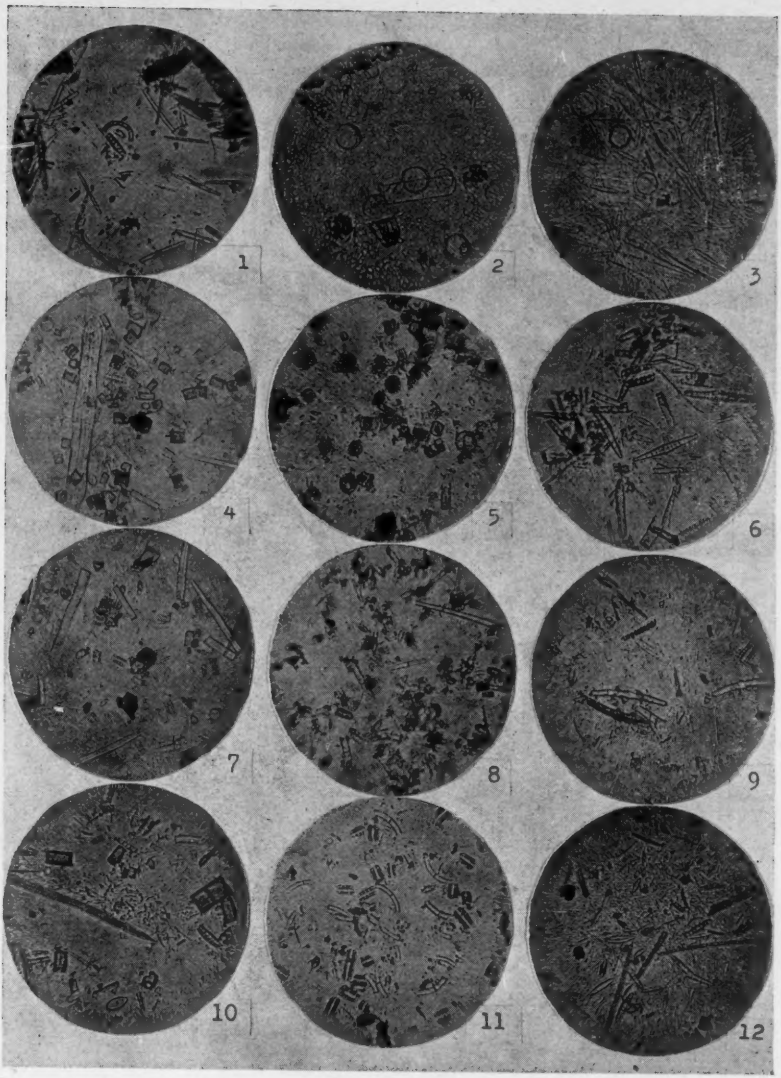
No. 8. As 5, but consisting of *Denticula pelagica*, *Denticula amphicephala* and *Melosira granulata* var. *Jonensis*, Samosir.

No. 9. As 5, but consisting of *Denticula pelagica*, *Duploneis subovalis* and *Pinnularia viridis*, Samosir.

No. 10. As 5, but consisting of *Denticula pelagica*, *Melosira granulata* var. *valida*, *Melosira granulata* var. *Jonensis*, *Duploneis subovalis* and a sponge spicule, Samosir.

No. 11. As 5, but consisting of *Denticula pelagica* and *Melosira granulata* var. *curvata*, Samosir.

No. 12. As 5, but consisting, among other species, of *Denticula pelagica* and *Denticula amphicephala*. Besides a few sponge spicules, Balige-Porsea plain.



MICROPHOTOS

(Explanation on facing page)

the volume is about 112 million cubic meters.

The total volume of diatomaceous earth of Samosir and the Balige-Porsea plain, including only the easily explorable deposits, can consequently be put at 125 million cubic meters. With a mean water content of 40 per cent in the various deposits of diatomite and a volume weight of 0.2 this gives about 15 million tons of absolutely dry material.

As the table shows, the diatomaceous earth deposits of Lake Toba, considering only the easily explorable ones, are quite extensive compared to those found elsewhere.

As the thickness of the pure diatomite layers reaches 75 to 100 centimeters, one must conclude that the environmental conditions during their formation have been very favorable. Among favorable circumstances should be reckoned a high SiO_2 content and also a high purity of the water of the lake. Undoubtedly the water of the lake must have contained much SiO_2 after the volcanic eruptions, as acid rhyolitic material rich in silica was ejected. The second condition too must have been fulfilled, because after the eruption the surrounding land was covered with tuff, so that plant life was very scant at first. Here one sees the association of large diatomite deposits and volcanic activity.

TABLE II. IMPORTANT DEPOSITS OF DIATOMITE (CALVERT-KENNY)

Description	*Estimated quantity in tons*
Lake Onangara—West of Australia	175,000
Chalk Mountain—New South Wales—Australia	250,000
Old Jallasjo lake—Sweden	480,000
Lake district of Kenya—East of Africa	620,000
Lake and stream district of Nova Scotia—Canada	1,000,000
Lüneburger heath—Germany	15,000,000
Isles of Mors and Fur—Denmark	33,000,000
Whitehills near Redrock Mountain—California	33,000,000
Mammoth—America	100,000,000
Province of Oran—North Africa	300,000,000*

* Considerably soiled by calcium carbonate.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 17, NO. 3, PP. 135–137
DECEMBER, 1947

SUGGESTIONS TO CONTRIBUTORS

TITLE

AUTHOR'S NAME
Institution
City and State

ABSTRACT

An abstract not longer than 250 words should accompany each paper. Abstracts should mention the more important new data or discoveries and the main conclusions of the paper.

INTRODUCTION

This brief style guide has been prepared by the editorial staff to aid contributors to the *Journal of Sedimentary Petrology*. It attempts to parallel the organization of a typical paper, although most papers should not, and in fact can not, be made to follow a stereotyped form. Similar guides, which use styles different from that of the *Journal of Sedimentary Petrology*, have been prepared for the U. S. Geological Survey (Wood and Lane, 1935), the Geological Society of America (Editorial Staff, 1937), and the American Association of Petroleum Geologists (Editorial Staff, 1945).

The introduction should contain a description of the area studied, the character of the problem, previous work if that can be summarized briefly and acknowledgments.

TITLE

The title should be long enough to cover the subject, but brief enough to be interesting. Subtitles are unnecessary. Few titles need be longer than 75 letters. Actually, a short descriptive title is much more apt to get a reader's attention than a long one; moreover, a short title can be repeated in its entirety in the running heads of the text pages.

HEADINGS

Primary

The word "Headings," used above, is a primary heading and is written in capital letters and centered.

Secondary

The word "Secondary," used immediately above, is a secondary heading and is written in capitals and small letters.

Tertiary.—Tertiary headings are usually unnecessary for the relatively short articles published in the *Journal of Sedimentary Petrology*. If required, however, they are written in capitals and small letters with an underscore for italics. Each begins a new paragraph, but is not an integral part of the first sentence.

WRITING

Organization

It is advisable to prepare a careful and detailed outline before writing is begun. Use of such an outline helps in organizing the paper and improves its clarity. Parts of the outline may also serve as headings.

Grammar

An effort should be made to write clearly and simply, taking special care to use short non-technical words wherever possible (Croneis, 1937). Sentences should be smooth and concise. Repeated rewriting, as well as correction following critical reading by colleagues, is usually helpful in recognizing and deleting unnecessary words. After stripping away the long technical words which overdress what may seem to be an important geological deduction, one often finds only a

small and not very original idea (Smith, 1922). Wood and Lane (1935, pp. 49–102) give many examples how sentences in geological reports can be simplified and clarified. Other hints are presented by Allbutt (1923) and Trelease and Yule (1937).

Form

Manuscripts submitted for publication should be typewritten and double-spaced on standard white 8½ by 11 inch paper. A 1½ inch margin at the left, bottom, and top, with 1 inch margin at the right of each page, leaves sufficient room for editorial comments and notes to the printer.

CITATIONS AND FOOTNOTES

Titles of published articles needed for citation should be arranged alphabetically by author and placed at the end of the paper. Proper abbreviations for the names of various journals and bulletins are given in a special pamphlet of the U. S. Geological Survey (Wood and Lane, 1935, pp. 22–29). Reference is made to the articles by author, date, and pertinent pages, as is done in this outline.

Footnotes usually are unnecessary because the information they contain can ordinarily be given more simply in the text itself. Their use should be restricted to the presentation of important facts which were discovered after the manuscript had been sent to press, and to unavoidable explanation of items in tables. Where necessary, the footnotes[1] are included in the text between parallel lines separating them from the text proper.

ILLUSTRATIONS

Preparation

One of the chief difficulties in the effective presentation of data or ideas by means of illustrations is that authors do not take the trouble to discover what happens to drawings or photographs in the process of printing. A pamphlet by Ridgway (1920) presents many helpful hints for the drafting of simple and effective illustrations. Symbols for various kinds of rocks and for map features are given in his plates 3 and 4. He also discusses the various processes of reproduction (pp. 72–90) and illustrates the effects of screening in the preparation of halftone cuts (pl. 6). One of the chief difficulties in effective presentation of drawings is that authors frequently fail to allow sufficiently for reduction. Remembering that most illustrations must be printed on regular pages, choose your line width and size of letters so they will stand out clearly after reduction. A reducing glass will help in making this estimate, though it should be remembered that the printed drawing usually is not so sharp as the original as seen through the glass.

Much additional information on illustrations is available (Moore, 1942). Moore's figures 5 and 6 show how an illustration may be clarified by omission of unnecessary detail. He also gives data on the visibility of lantern slide lettering (Moore, 1942, figs. 2, 7, 8.)

Kind

All photographs and fold-ins are termed plates, because they usually are printed on paper of special quality or size. Line drawings which occupy part or all of a text page are figures.

Titles and Explanation

A short descriptive title and usually one or two short sentences of explanation are needed for each illustration. They should be typed at the appropriate place in the manuscript between lines extending completely across the page.

CONCLUSIONS

If contributors will follow these suggestions, the work of the editors will be lightened and the time between the writing of a paper and its publication may be shortened. Information on the cost of reprints will be supplied when galley proof is returned to the author.

[1] Do not use footnotes if their use can be avoided.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 17, NO. 3, P. 138
DECEMBER, 1947

SECOND INTERNATIONAL CONFERENCE ON SOIL MECHANICS AND FOUNDATION ENGINEERING

The Second International Conference on Soil Mechanics and Foundation Engineering will be held at Rotterdam, Holland, during the summer of 1948. This conference is to be sponsored by the Government of the Netherlands. The tentative date is the week of June 21, 1948.

Dr. Karl Terzaghi of Harvard University is President of the Conference and Mr. T. K. Huizinga of Delft, Holland is Secretary.

To stimulate interest and to encourage the preparation of papers suitable for presentation at the Conference, the National Committee on Soil Mechanics Representing the United States of America has been appointed. Professor P. C. Rutledge of Northwestern University is Chairman of this committee.

The National Committee has been divided into a number of technical Subcommittees, based on subject matter. The Chairman of the U. S. National Committee invited the Geological Survey to appoint an official representative whose duties are to keep geologists and geological societies informed of all arrangements for the conference, and to secure papers from geologists on pertinent subjects. Mr. Edwin B. Eckel, Chief, Section of Engineering Geology, U. S. Geological Survey, Box 2858, Lakewood Branch, Denver 15, Colorado, has been named as this representative.

The Committee's cordial invitation to geologists to join in their work is based on its belief that "the quantitative engineering studies of the behavior of soils are attracting increasing interest among geologists, and that a closer alliance of interests and research works between engineers and geologists is desirable." This attitude should be both welcomed and deeply appreciated by geologists, many of whom have been keenly aware of the gap that has existed heretofore between the fields of geology and soils, and who desire to keep abreast of developments in the soils field if not, indeed, to close the gap.

Worthwhile papers on any subject that falls within the scope of the Conferenc are earnestly solicited from geologists. For papers to be published before the Conference, the December 15, 1947 deadline for receipt of final manuscripts by the U. S. National Committee is already too close. There is, however, a strong likelihood that papers will be accepted up to the time of the Conference for subsequent publication.

Further information on any phase of the Rotterdam meetings, on the work of the U. S. Committee, or on the submission of papers, can be obtained from Mr. Eckel or from Mr. Howard P. Hall, Secretary, U. S. National Committee on Soil Mechanics, Northwestern University, Evanston, Illinois.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 17, No. 3, P. 139
DECEMBER, 1947

REVIEW

ANDRE CAILLEUX. *Distinction des Galets Marins et Fluviatiles*, 1945, Bulletin de la Societe geologique de France, 5th serie, t. XV, pp. 375–404.

The characteristics found to be most useful for distinguishing between marine and fluviatile gravels were shape and inclination.

Shape measures are "flatness" (length plus breath divided by twice the thickness) and "assymetry" (the distance, in the dominant plane of the pebble, from the point of intersection of the intermediate axis with the long axis to the furthest extremity of the long axis, divided by the long axis). Inclination is the dihedral angle formed by the stratification plane and the dominant plane of the pebble.

Measurements based on about 4000 pebbles from 52 formations (Recent to Paleozoic) show that the inclination of the average pebble is greater in fluviatile formations (around 15–30 deg.) than in marine formations (around 2–12 deg.). The median inclination is the most diagnostic. While a weak inclination necessarily indicates a marine deposit, a strong inclination might be due to imposition of a fluviatile type inclination on beach deposits by marine currents of constant direction.

Measurements of some 12,000 pebbles from 83 formations show marine deposits to be characterized by pebbles having a high flatness and low assymetry while fluviatile deposits show converse relations. The criterion is valid, however, only if: 1) pebbles of the same rock type are compared, 2) an optimum size is selected (Quartz 5–6 cm. for flatness and 3.5–4.5 cm. for assymetry), 3) an optimum per cent grade be chosen for diagnosis (Quartz 85% grade for flatness and 30–50% grades for assymetry). Deviation from these prescribed conditions results in overlapping of the marine and fluviatile indices.

Cailleux's results contradict those of R. M. Grogan (Shape Variation of Some Lake Superior Beach Pebbles, 1945, *Jour. Sedimentary Petrology*, Vol. 15, No. 1, pp. 3–10). In a study of the beach of Torre Annunziata, Cailleux found that pebbles of compact lava from a known outcrop source suffered progressive increase in flatness with distance of transport down the beach. At the foot of the outcrop the pebbles had a flatness of 2.2. At 300 meters in the direction of transport the pebbles attain a flatness of 2.8. On the other hand, Grogan found a progressive increase in mean sphericity of rhyolite beach pebbles with distance of transport. In 2200 ft. of transport, the mean sphericity increased from .55 to .64. These two results are mutually exclusive since an increase of sphericity corresponds to a decrease in flatness.

The data presented in this paper are well worth further study by American geologists. Perhaps further study along these lines will sharpen the limits of the marine and fluviatile domains and reveal the dynamic factors which control the limiting conditions of size and per cent grade.

WILLIAM J. PLUMLEY
The University of Chicago

Journal of Sedimentary Petrology

INDEX TO VOLUME 17

Abel, O., cited 76
Aberdeen, E., cited 33
Abrasional wear, degree of 69
Accessory minerals 30
Adkins, W. S., cited 72
Allbutt, T. C., cited 136
Allen, P., article by 3
Allen, P., cited 5, 7
Allison, V. C., cited 46
Allogenic frequency 3
Allogenic grade size and frequency 3
Amphibole 15
Analyses, chemical 45
Analyses, mechanical 13, 70
Analyses, mineral 9
Angel Cave, Victoria, Australia 41
Antlers sand 70
Aragonite 62
Arkose, basin type 97
Arkose, platform type 96
Autogeosyncline 110

Bailey, E. B., cited 92, 108
Baker, G., article by 39
Baragwanth, W., cited 63
Barred basins 110
Barrell, J., cited 99, 120
Barton, D. C., cited 99
Basin arkoses 97
Basin limestone 110
Basin sandstones 93, 97
Basin shales 105
Basins, open 110
Bass, N. W., cited 99
Bathyal gravels 123
Beach gravel 123
Beach slopes and ripples 18
Black, M., cited 33, 64
Bone Spring limestone 111
Boswell, P. G. H., cited 31
Brady, L. F., cited 25
Brajnikov, B., cited 3
Bramlette, N. M., cited 102
Branson, C. C., cited 99
Brockmann, C., cited 130
Broken Hill, New South Wales, pisoliths in 61
Bromoform 9
Brotherhood, G. R., article by 77
Bryan, W. H., cited 63
Bucher, W. H., cited 18, 66
Burvill, G. H., cited 17

Cailleux, A., cited 120
Cailleux, A., review of article by 139
Calcium carbonate, factors controlling deposition 45
Calvert, R., cited 130
Carman, J. E., cited 99
Carroll, Dorothy, article by 8
Casteret, N., cited 39
Cave, deposits in 43
Cave pearls 49
Cave temperatures 46
Cave waters, analysis of 45
Cayeaux, L., cited 32
Chalk bluff formation 111
Chemical properties of sediments 31
Chert 110
Chillagoe Cave, Queensland 58
Chugwater sandstone 94
Citric acid as cleaning agent 84
Classification of sediments 31
Classification of shale 103, 105
Clay petrography 31
Cleaning mineral grains for petrographic study 83
Coal partings in stylolite seams 114
Cockatoo sand 11, 12
Coconino sandstone 23
Cody sandstone 98
Color chart, committee on 35
Concentric banding in pisoliths 57
Conglomerates, characteristics of 120
Conglomerates, marine 121
Continental conglomerate 125
Contributions to the Journal of Sedimentary Petrology 87
Conunurra clay 9, 11
Coombs, H. A., cited 39
Cooper, J. R., cited 99
Correlation between allogenic grade size and allogenic frequency in sediments 3
Correlation, statistical 6
Coulson, A., cited 66
Crescents, current, origin of 73
Croneis, C. G., cited 135
Crowley, A. J., cited 99
Crystalline limestone 109
Cullison, J. S., cited 99
Cummings, E. R., cited 102
Cumulative curves 80, 81
Current crescents in the Triassic Mcenkopi formation 73
Current crescents, origin of 73
Curves, frequency 80, 81

Dake, C. L., cited 99
Dapples, E. C., article by 91
Dapples, E. C., cited 106, 109
Davidson, S. C., cited 39
Deane, C., cited 45
De Ford, R. K., cited 30
Delta gravel 125
Demarest, D., article by 18
Dense limestone 109
Deposition of calcium carbonate 45
Desert gravels 126
Development of tracks in sand 23
Diagenesis 31
Diatomaceous deposits at Lake Toba 129
Diatomite, analysis 132
Diatomite, important deposits 134

Diatomite, microphotos of 133
Dion, H. G., cited 83
Dryden, C., cited 99
Dryden, L., cited 99
Du Bois, E. P., cited 111

Eagle sandstone 98
Edson, F. C., cited 99
Edwards, A. B., cited 66
Emery, K. O., article by 87
Emmons, R. C., cited 39
Emmons, W. H., cited 64
Environmental significance of conglomerates 119
Environmental significance of shales ... 101
Environments of deposition 121
Environments of limestone deposition. 109
Erdman, E., cited 67
Etheridge, R., cited 58
Evans, P., cited 17
Experiments on the development of tracks in fine crossbedded sand 23

Fettke, C. R., cited 99
Fisher, R. A., cited 7
Foreman, F., cited 99
Fragmental limestone 109
Frequency, allogenic 3
Frequency curve, derivation of 79
Frequency curves 80, 81
Frontier sandstone 98
Frostick, A. C., article by 39

Galliher, E. W., cited 99
Garnet 71
Geochemical decomposition 4
Geosynclinal limestone 111
Geosynclinal sandstones 97
Geosynclinal shales 105
Gibson, D., cited 100
Gilbert, C. M., article by 83
Giles, A. W., cited 99
Gilligan, A., cited 72
Glacial gravels 126
Glen Rose limestone 68, 72
Graham, W., cited 99
Grain size distribution 30
Gravels, beach 123
Gravels, delta 125
Gravels, desert 126
Gravels, neritic 121, 123
Grawe, O. R., cited 99
Graywacke 97
Gregory, H. E., cited 120
Griffiths, J. C., article by 29, 77
Griffiths, J. C., cited 31
Grim, R. E., cited 102
Gripenberg, S., cited 101
Grogan, R. M., cited 127, 139
Grout, F. F., cited 83

Halbouty, M. T., cited 33
Hamblin, R. H., cited 30
Hand specimens, description of 29
Harrison, T., cited 43
Hatch, F. H., cited 62
Hayman, R. J., cited 17
Heavy mineral frequencies 70
Heavy minerals 9, 10, 30, 70
Heavy minerals, Australia 15
Heavy minerals, cleaning of 83
Heavy residues of soils from the Lower Ord Valley, Western Australia 8
Hematite 71
Hess, F. L., cited 39
Hill, R. T., cited 68
Holmes, A., cited 85

Ilmenite 71
Imlay, R. W., cited 99
Intracratonic basins 111

Jack, R. L., cited 58
Jackson, A. M., cited 99
Johannsen, A., cited 31
Johnson, D. W., cited 22
Johnson, J., cited 48
Jones, O. T., cited 92, 108, 110
Journal of Sedimentary Petrology, contributions to 87

Kay, G. M., cited 92, 104, 110
Keller, W. C., cited 39, 99
Kenny, E. J., cited 130
King, P. B., cited 111
Klein, W. C., cited 134
Krumbein, W. C., article by 101
Krumbein, W. C., cited 30, 77, 79, 82, 94, 98, 107, 109, 120
Krynine, P. D., cited 30, 92, 97, 108

Lake Toba (Sumatra) 129
Lamar, J. E., cited 99
Landon, R. E., cited 120
Lane, B. H., cited 135
Leathercock, C., cited 99
Lee, W. T., cited 39
Leucoxene 71
Levorsen, A. I., cited 33
Limestone, basin 110
Limestone, crystalline 109
Limestone, dense 109
Limestone, environments 109
Limestone, fragmental 109
Limestone, geosynclinal 111
Limestone, normal marine 110
Limestone, platform 110
Limestone reefs 111
Limestone, saccharoidal 109
Linck, G., cited 62
Lowenstamm, H. A., cited 111
Lowman, S. W., cited 109
Lucas, E. L., cited 99

Mackin, J. H., cited 39
Maddox, D. C., cited 108
Magnetite 71
Majeed, M. A., cited 17
Manger, G. E., cited 100
Mansfield, C. R., cited 120
Mantinea clay 9, 11
Marine conglomerate 121
Mathematical derivation of the unique frequency curve 77

Matheson, R. S., cited 10
McCartney, G. C., cited 100
McKee, E. D., article by 23
McKee, E. C., cited 25, 100
McKinstry, H. E., cited 39
McQueen, H. S., cited 34
Mechanical analyses 13, 70
Meland, N., cited 100
Melhuish, C. A., cited 45
Mellor, J. W., cited 78
Mencher, E., cited 100
Mercury value for separating heavy minerals 86
Meruin sandy loam 9
Merwin, H. E., cited 48
Mesaverde sandstone 95
Miller, H. W., cited 100
Milner, H. B., cited 32
Mineral analysis 9
Mineral examination 9
Mineral grains, cleaning of 83
Minerals, accessory 30
Moenkopi formation 73
Moore, C. A., cited 136
Morgan, G. D., cited 100
Mudflat deposits in Moenkopi formation 75
Munsell color system 35
Murrendal caves, Victoria, Australia 58

Needham, C. E., cited 100
Neritic gravels 121, 123
Normal marine limestone 110
Northrop, S. A., cited 39
Nutting, P. G., cited 100

Ockerman, J. W., cited 100
Oil industry and sedimentary petrography 29
Ooliths (see pisoliths) .....
Ord River, Australia 7, 9
Ord sandy loam 11
Oxalic acid as cleaning agent 84

Paluxy sands 68
Particle shape in conglomerates 120
Patnode, W. H., cited 34, 102
Payne, J. N., cited 100
Payne, T. G., cited 102
Peabody, F. E., article by 73
Peabody, F. E., cited 28, 76
Petrography of clays 31
Pettijohn, F. J., cited 32, 92, 108, 112
Phi notation 78, 94
Phosphoric acid as cleaning agent 83
Physical properties of sediments 31
Piedmont gravels 125
Pisoliths and ooliths from some Australian caves and mines 39
Pisoliths, growth of 52
Pisoliths in caves 48
Pisoliths in mines 60
Pisoliths, internal nature 53
Pisoliths, origin of 62
Pisoliths, properties of 48
Pisoliths, structure of 53
Platform arkoses 96
Platform limestone 110
Platform sandstones 93
Platform shales 105
Plimsol line 44
Plumley, W. J., review by 139
Polished surfaces on pisoliths 50, 64
Pond, A. W., cited 34
Powers, S., cited 34
Pye, W. G., cited 100
Pyroxene 15

Quartz 71
Quartz-glauconite sandstone 94
Quartz-feldspar sandstone 95
Quartz-iron oxide sandstone 94
Quartz-mica sandstone 95
Quartzose sandstones 93

Rastall, R. H., cited 62
Reed, R. D., cited 100
Reef limestones 111
Reptile tracks in sand 24
Restricted transport 3, 4
Reviews 139
Rhomb angles in ripples 19
Rhomboid ripple marks and their relation to beach slope 18
Rhomboid ripple marks, origin of 20
Ridgeway, J. L., cited 136
Ripple marks, rhomboid 18
Rittenhouse, G., cited 30, 82, 107
Rock color chart, committee on 35
Routine for shale examination 106
Rubey, W. W., cited 103
Russell, R. D., cited 17
Rutile 71
Ruttner, F., cited 130

Saccharoidal limestone 109
Sandstone, glauconitic 94
Sandstone, iron oxide type 94
Sandstone, quartzose 93
Sandstone types and asscciated depcsitional environments 91
Sandstones, geosynclinal 97
Schade, H., cited 63
Scott, G., cited 68
Sea Girt, N. J., ripples at 19
Second International Conference on soil mechanics 138
Sedimentary petrography and the oil industry 29
Selective sorting 4, 6
Separate vs. mutual transport 5
Shale, basin type 105
Shale, chemical analysis 102
Shale, classification of 103, 105
Shale, color of 102
Shale, examination 106
Shale, mineral analysis 102
Shale, platform type 105
Shale, properties of 101
Shales and their environmental significance 101
Shales, geosynclinal 105
Shaub, B. M., article by 114
Shaub, B. M., cited 118

Shrock, R. R., cited 102
Sidwell, R., article by 68
Sidwell, R., cited 100
Slopes, beach 18
Sloss, L. L., article by 109
Sloss, L. L., cited 34, 108
Smith, G. O., cited 136
Smithson, F., cited 30
Soil residues, source of 16
Soils, heavy minerals of 14
Soils, residual minerals in 8
Sonstadt solution 86
Splash cups in caves 46
Stalagmites 46
Statistical correlation, effects of shape and density on 6
Staurolite 71
Stearns, M. D., cited 100
Stirling's interpolation formula 77
Stockdale, P. B., cited 114
Stylolites 114
Stylolite seams 114
Sud, C. P., article by 86
Suggestions to contributors 135
Sundance sandstone 94

Taliaferro, N. L., cited 34
Tartaric acid as cleaning agent 84
Teakle, L. J. H., cited 17
Tectonic factors in sedimentation 92, 104, 105
Teichert, C., cited 17
Temperatures, cave 46
Tercier, J. J., cited 104
Thin section analysis 30
Thompson, W. D., cited 100
Thomsen, H., cited 99
Thoulet solution 86
Tickell, F. G., cited 34
Tieje, A. J., cited 100
Tombigbee sandstone 94
Tomlinson, C. W., cited 100
Tourmaline 15
Transport, restricted 3
Transport, selective 4
Transport, unrestricted 3
Trask, P. D., cited 31, 102
Travertine, analysis of 61
Travis Peak formation 70
Trelease, S. F., cited 136
Trinity sediments, environment of deposition 72
Trinity sediments of North and Central Texas 68
Trowbridge, A. C., cited 120
Twenhofel, W. H., article by 119
Twenhofel, W. H., cited 31, 39, 67, 101, 108, 110

Unconformities and gravels 126
Unrestricted transport 3
Use of acids for cleaning mineral grains 83

Van Bemmelen, R. W., cited 134
Van der Marel, article by 129
Van Hise, C. R., cited 34
Von Engeln, O. D., cited 128

Wadell, H., cited 120
Walcott, C. D., cited 127
Waldschmidt, W., cited 30
Walther, J., cited 73
Wanless, H. R., cited 100
Wentworth, C. K., cited 120
Whitehouse, W., cited 17
Williamson, E. D., cited 48
Willruth, K., cited 73
Wilman, H. B., cited 100
Winchell, A. N., cited 34
Wingate sandstone 94
Wood, G. M., cited 135
Woodford, A. O., cited 20

Yule, E. S., cited 136

Zircon 15, 71

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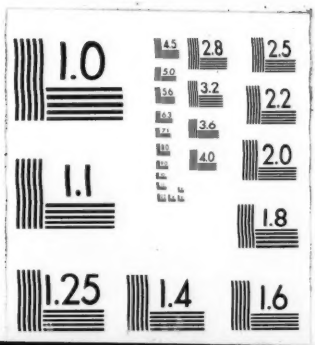
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